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THESIS

STUDY OF VARIATION IN FLOW THROUGH

STRAIT OF GIBRALTAR

by

Johnny Marion Sears

June 1968

Thesis
S40577

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STUDY OF VARIATION IN FLOW THROUGH STRAIT OF GIBRALTAR

by

Johnny Marion Sears
Lieutenant Commander, United States Navy
B.S., Middle Tennessee State College, 1955

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
June 1968

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Thesis S40577 c.2

Averaged oceanographic station data are used to describe the seasonal variation of salinity and temperature in the Strait of Gibraltar area. Seasonal sections of salinity suggest that winter is the season of maximum outflow of the Mediterranean Water, and that summer is the season of maximum inflow of the Atlantic Water. The seasonal sections show how the high salinity water is deflected to the north along the Iberian Peninsula, and show that the salinity maximum near 1000 meters, west of Portugal, is maintained through all seasons.

The seasonal currents of the bottom layer west of the sill are computed. These are used with the cross-sectional area across the Strait to compute the seasonal mass transport of the outflowing layer. The total annual outflow thus obtained compares favorably with earlier calculations.

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I. INTRODUCTION

A. Statement of the problem.

It is well established (Sverdrup, 1942) that high salinity Mediterranean water flows outward through the Strait of Gibraltar beneath the less saline Atlantic water and spreads as an intermediate layer over large areas of the North Atlantic Ocean. The primary purpose of this study is to determine the cycle of the flow through the Strait, and to investigate the seasonal changes in high salinity Mediterranean Water spreading into the eastern North Atlantic Ocean; relationships between these flows and atmospheric parameters are sought. Additional objectives of this study are to determine the seasonal hydrographic structure of the Strait, the mechanism of the water exchange between the Mediterranean and the Atlantic, and the factors affecting this mechanism.

Averaged sections of temperature and salinity have been constructed which show the seasonal variation of these parameters in the horizontal and vertical directions. In addition, seasonal sections of sigma-t (σ_t) surfacesare used to calculate the current along the downward sloping bottom extending west of the sill, using a technique proposed by Dietrich (1956). Seasonal sections of atmospheric parameters, sea level pressure and surface winds, are used to show atmospheric effects on the currents through the Strait. Seasonal horizontal charts of salinity, for various depths, are used to demonstrate the spreading of the

Mediterranean water into the eastern Atlantic Ocean, and to trace the effects of "upwelling" along the adjacent coasts of Portugal and Morocco.

The data were obtained from the National Oceanographic Data Center (NODC), via Fleet Numerical Weather Facility (FNWF) Monterey, and contained all available oceanographic station data for the past 60 years. It is understood that data collected by France and Spain are not included. Averaged values of temperature and salinity were obtained by averaging all available observations over one degree Marsden squares for each season of the year. Seasons are identified as follows:

Winter	January - March
Spring	April - June
Summer	July - September
Fall	October - December.

The area selected for study extends between 32 - 40 degrees North Latitude, and 0 - 15 degrees West Longitude. The seasonal averages of salinity and temperature were computed using FNWF's Control Data Corporation 6500 digital computer, utilizing an averaging program prepared by the Mellonics System Development Division, Litton Systems, Inc., (Griswold et al., 1968).

There were definite limitations in using averaged data to describe the variations in temperature and salinity. These limitations involve considerations of data density (1) in space and (2) in time.

(1) If a space average is to be meaningful it must be composed of a reasonable number of observations well distributed over the area.

In the construction of sections this criterion was not always satisfied; in fact, some data points are composed of a single sounding.

(2) It has been assumed that soundings are evenly spaced in time throughout the season. In general, this is not the source of a large error, except when the averaged quantity is obtained using a few soundings closely spaced in time when significant time variability is present. In addition, if the averaged quantity is determined by using only data obtained far from the midpoint during a rare atmospheric condition, it would not, probably, be representative of average conditions for that season.

B. Summary of previous work.

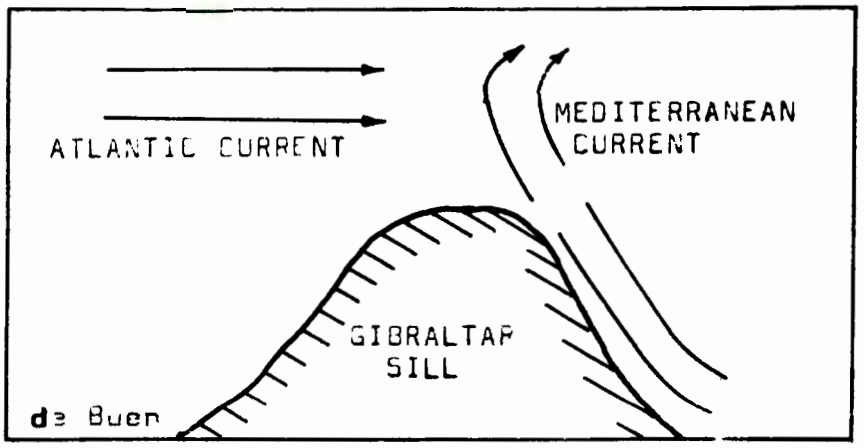
The description and explanation of the complex current and water exchange system through the Strait of Gibraltar has been the subject of several oceanographic studies. The first suggestion that an undercurrent flowed through the Strait of Gibraltar into the Atlantic Ocean was made by Dr. Th. Smith in 1684. The question whether there is an undercurrent or not, was not resolved until D'Urville made temperature observations in the western Mediterranean Basin and found that the temperature of the Mediterranean Bottom Water was near that of the surface water in the north portion of the western Mediterranean Sea at the coldest time of the year. He concluded that the bottom water must be formed by convection currents in the northern portion of the western Mediterranean Sea during the winter season. Nielsen (1912) used observations taken in the northwestern Mediterranean Sea near

the French Riviera to show that convection currents reached the bottom during the winter of 1909. He determined, from potential temperature considerations, that the depth of convective mixing varied with the cooling at the surface. Nielsen concluded that the formation of the bottom water is intermittent and mixes completely to the bottom only under extreme surface cooling in the winter season.

According to Nielsen (1912), the fact that Mediterranean water is of greater salinity than the Atlantic water is sufficient to show that evaporation is greater than precipitation and runoff. If a constant water level is assumed for the Mediterranean Sea, a net inflow must occur to replace the water lost to excess evaporation. A net inflow of water does occur from the Black Sea, but it is much too small in volume to account for that lost due to excess evaporation (Sverdrup, 1942).

R. de Buen (1926) attempted to show that the submarine ridge across the Strait of Gibraltar effectively restricts the westward flow of the Mediterranean Water. He presented a model of the currents and salinity distribution across the sill area, shown in Figure 1. A thorough investigation of observations taken west of the sill area proved de Buen's hypothesis was incorrect in some parts, as shown by Schott (1928).

Nielsen (1912) presented salinity sections for February and June, shown in Figure 2. These sections, west of the sill, were constructed from data taken by the "Thor" Expedition (1908 - 1910) and show the sloping interface between the Atlantic and Mediterranean water masses, as well as the spreading of the high salinity Mediterranean Water along



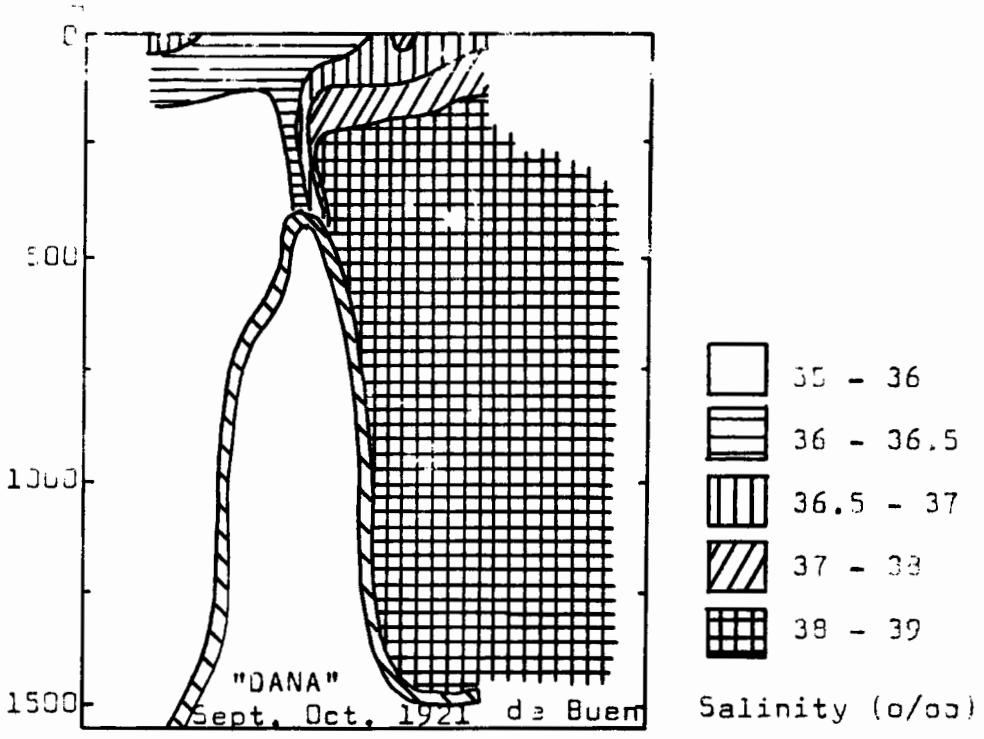
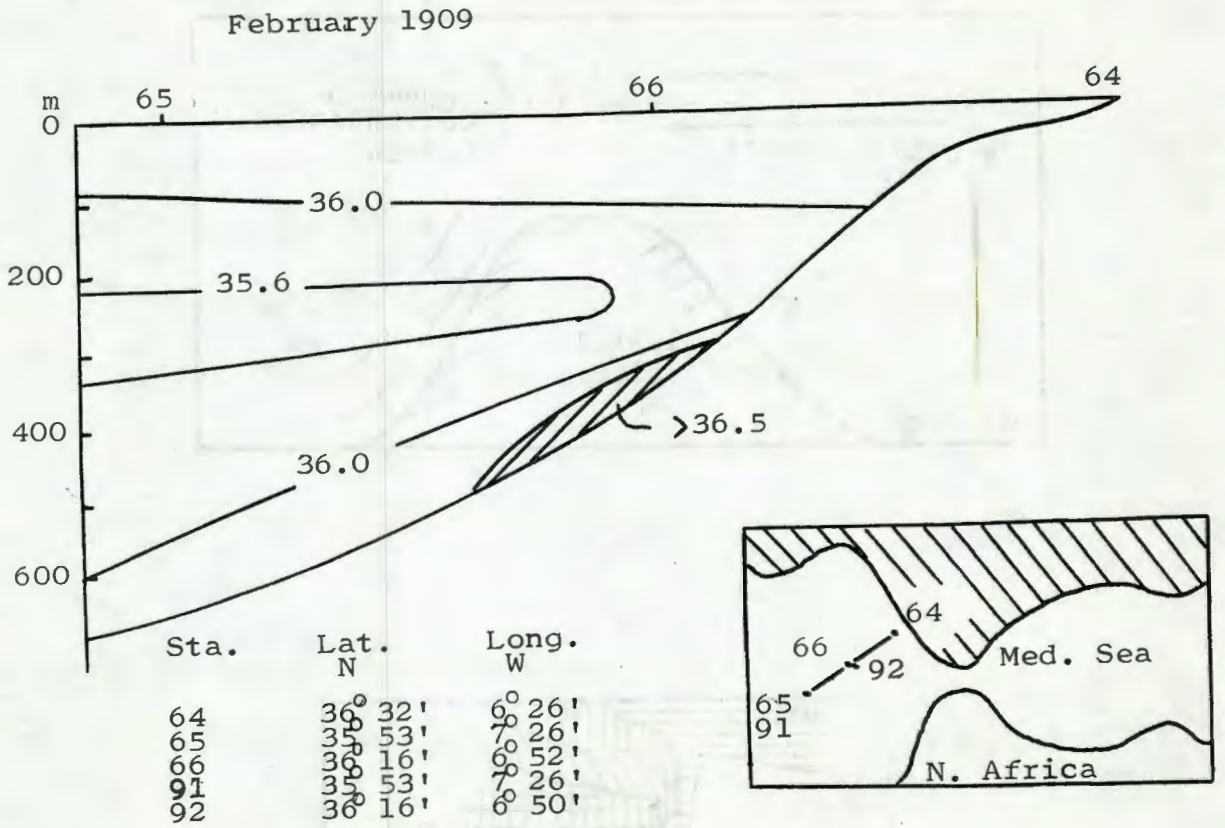


Figure 1. de Buen's model of Strait of Gibraltar.



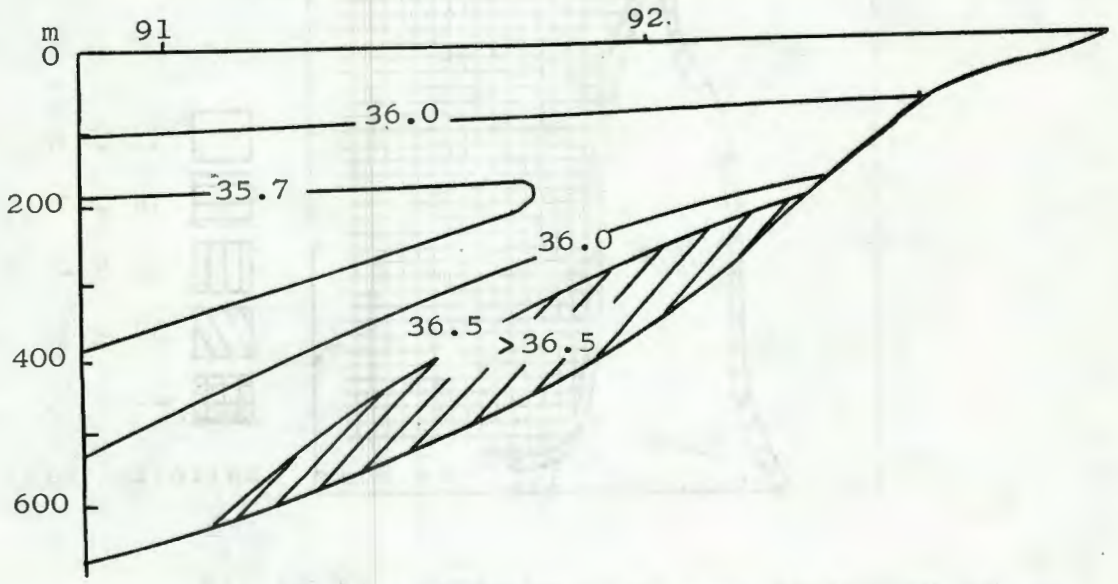


Figure 2. Salinity section west of Strait of Gibraltar. (o/oo)(after Nielsen, 1912) (see inset for station location)

the bottom. Nielsen noted that the volume occupied by the (outflowing) Mediterranean Water was much greater in June than in February; therefore, he concluded that the outflow is greatest in the summer season.

Schott (1928) used data collected by several expeditions in different years to construct sections of salinity and temperature for the Gibraltar Strait area. This classical oceanographic work clearly indicates the water exchange system between the Atlantic Ocean and Mediterranean Sea. These data represent a large percent of those data available at the present time for this area.

Figure 3 shows the typical end-of-winter distribution of salinity and temperature through the Strait, as presented by Schott (1928). The sloping interface between inflowing and outflowing water is shown with an indicated depth near 125 meters over the sill area. In the upper layer, Atlantic water (with a salinity slightly above 36.25 o/oo and a temperature greater than 14.5 C) flows eastward into the Mediterranean Sea. In the subsurface layer, Mediterranean Water (with a salinity near 37.75 o/oo and temperature near 13.5 C) flows westward across the sill and follows the bottom sloping downward toward the Atlantic Ocean.

The early summer sections of salinity and temperature, shown in Figure 4, indicate inflowing Atlantic Water with a salinity slightly less than 36.25 o/oo and a temperature range from 14.5 to 17.5 C. The indicated outflow has a salinity near 37.50 o/oo and a temperature

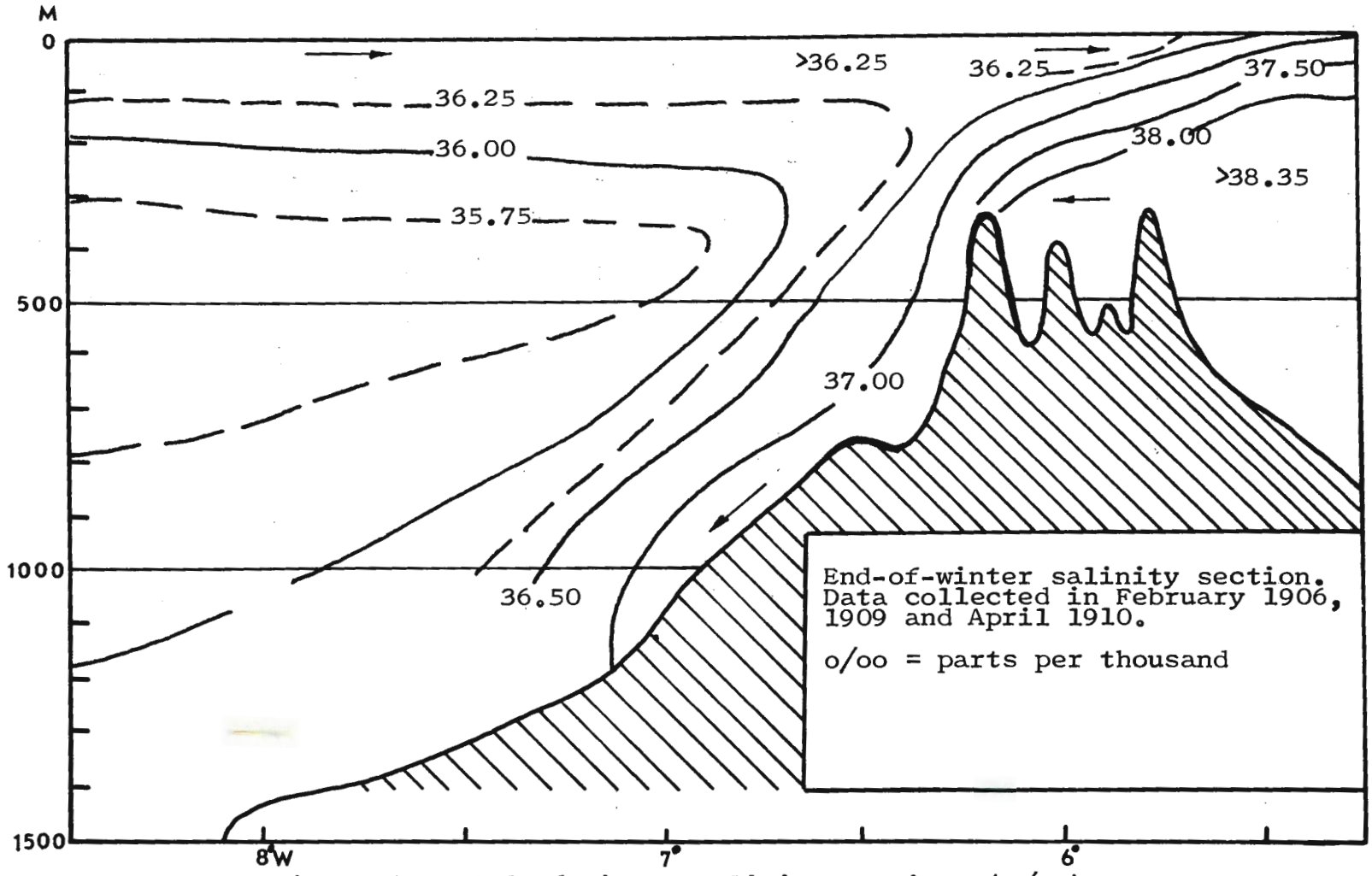


Figure 3a. End-of-winter salinity section. (o/oo)
(after Schott, 1928)

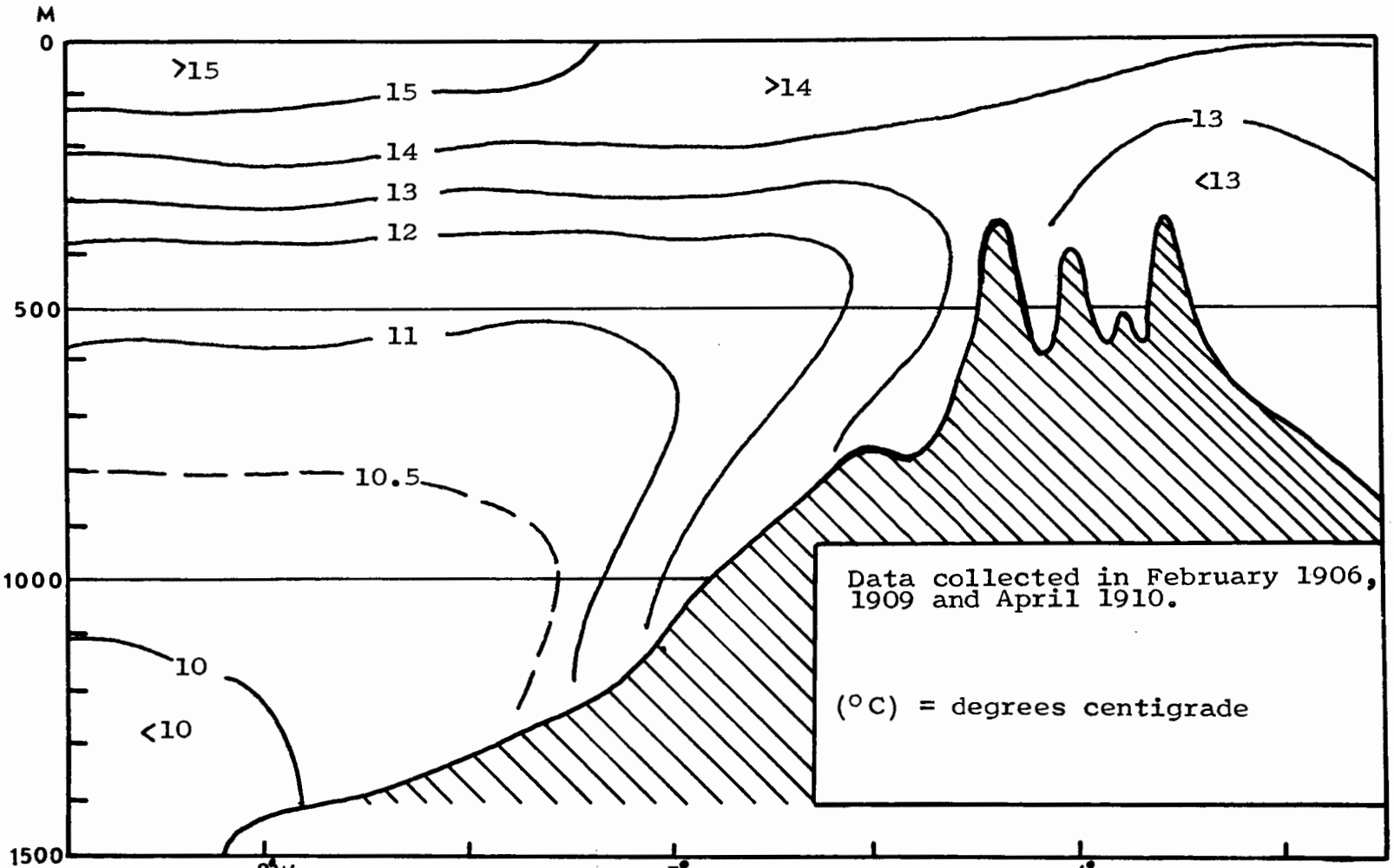


Figure 3b. End-of-winter temperature section. (°C)
(after Schott, 1928)

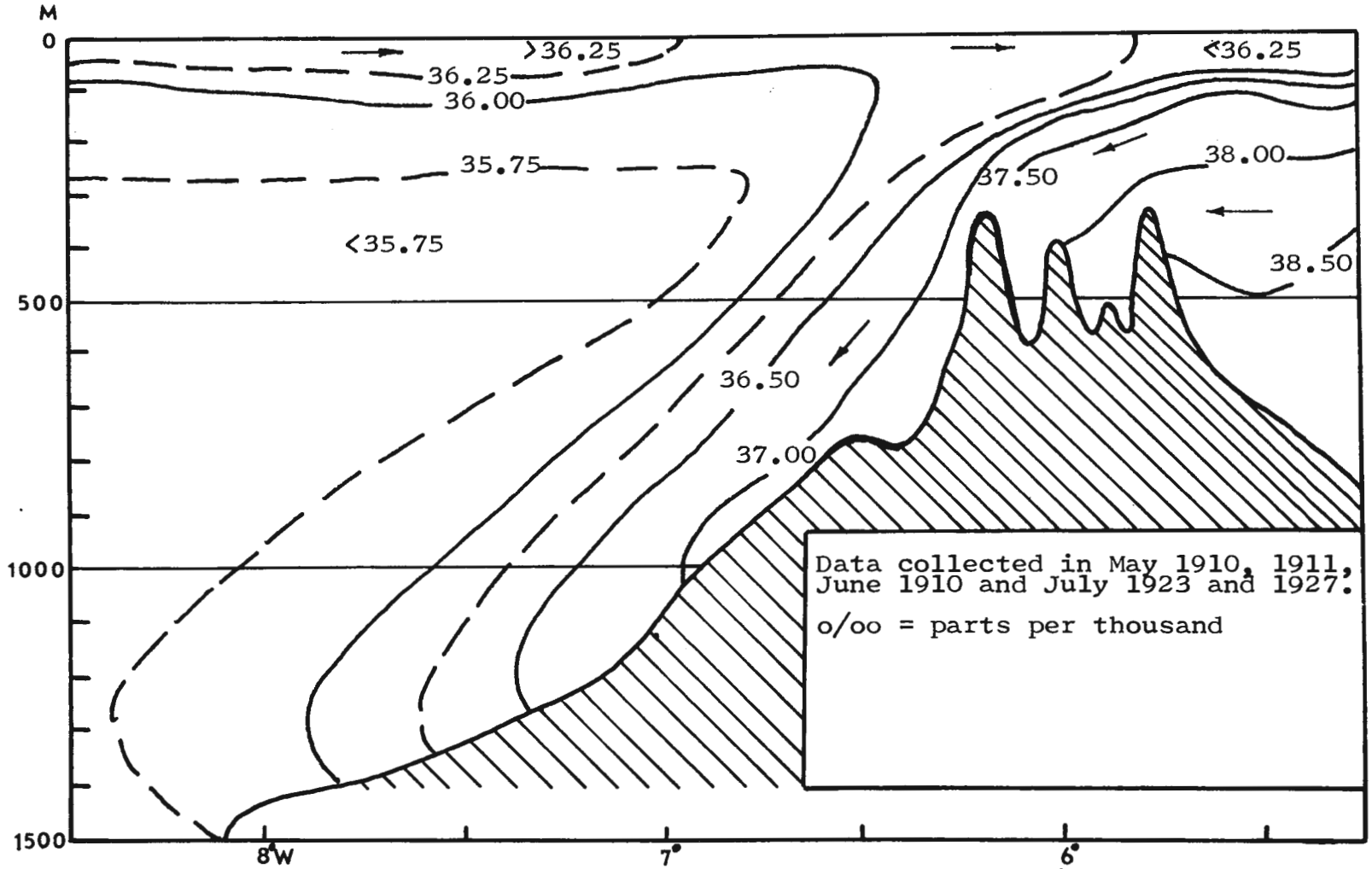


Figure 4a. Early summer salinity section (o/oo) (after Schott, 1928)

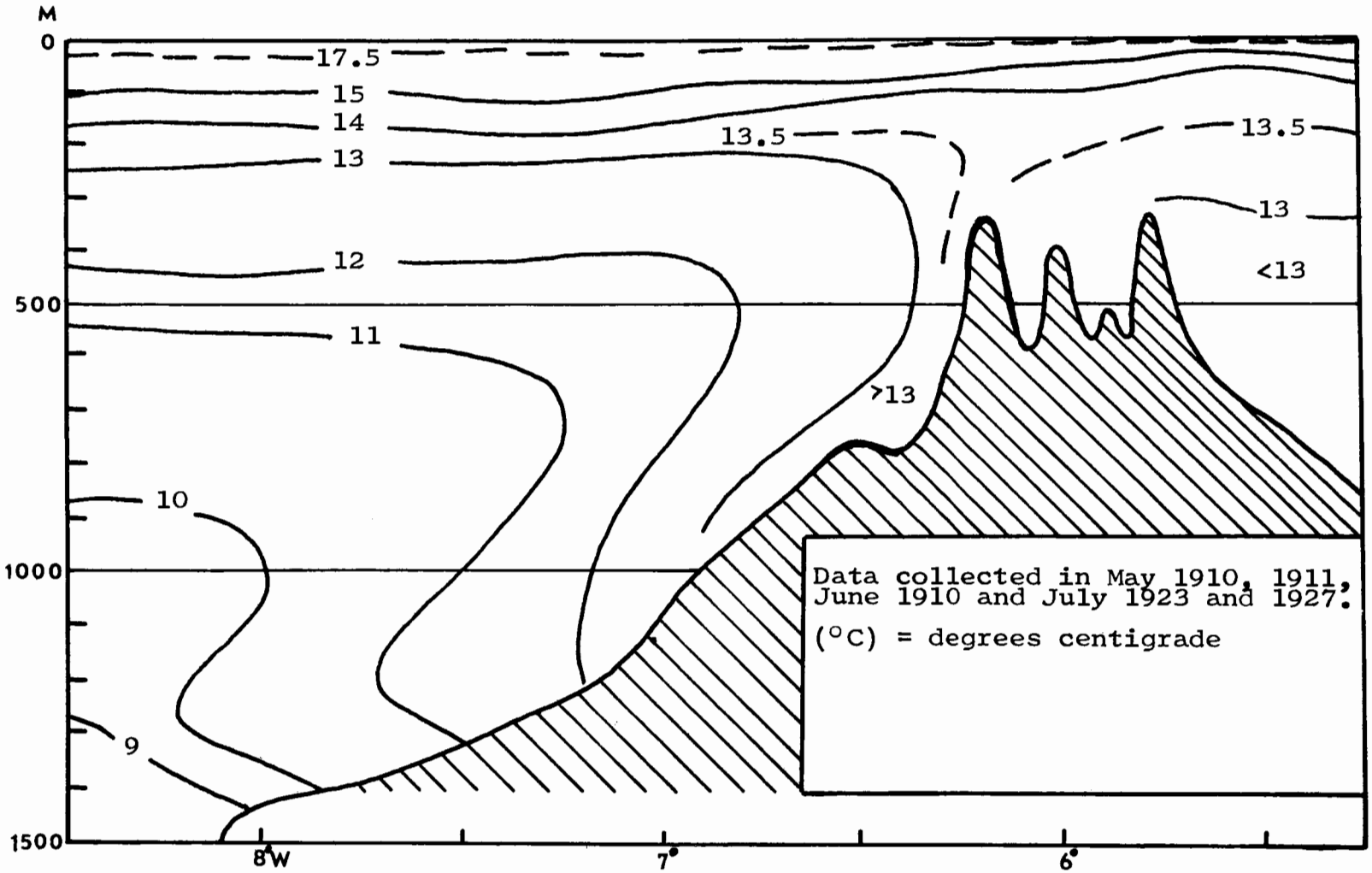


Figure 4b. Early summer temperature section. (°C)
(after Schott, 1928)

of 13.5 C, with the interface shown at a depth of approximately 200 meters over the sill area.

The late summer sections of salinity and temperature by Schott, Figure 5, indicate the inflowing water to have a salinity of 36.25 o/oo near the surface but slightly less than 36.00 o/oo in the lower portion. The inflow has a temperature range from 13.5 to near 20 C. The outflowing layer is shown as a reduced thickness with a salinity near 37.00 o/oo and a temperature near 13 C. The salinity section, Figure 5a, shows a salinity minimum area extending eastward over the sill area. Although this feature appears on the winter and early summer salinity sections, it is much more pronounced in late summer.

Lacombe and Tchernia (1960) presented the summer salinity distribution through the Strait between 0 and 25 degrees West Longitude, shown in Figure 6. This section, prepared from data obtained from several oceanographic expeditions during 1955 - 1958, shows clearly that salinities less than 36.00 o/oo do not exist inside the sill. It is of interest that, except for the salinity minimum above the sill, Schott's late summer section, Figure 5a, agrees well with that of Lacombe and Tchernia, Figure 6. There were no sections available for the spring and fall seasons.

Frassetto (1964) presented an excellent account of the short-period vertical displacements of temperature and salinity in the Strait of Gibraltar. Data from several expeditions were used with profiled temperature data obtained by use of a towed thermistor chain to show short-

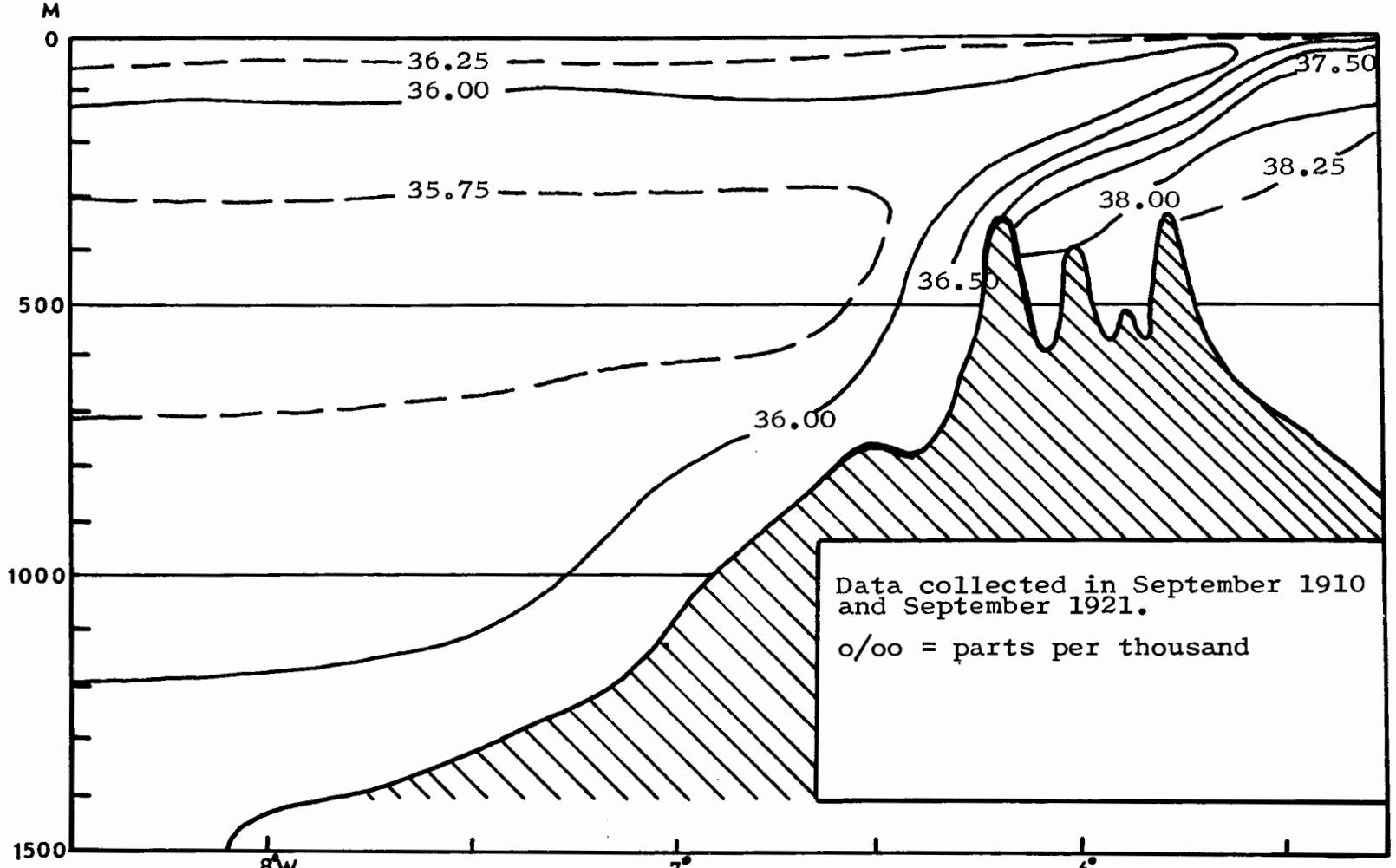


Figure 5a. End-of-summer salinity section. (o/oo) (after Schott, 1928)

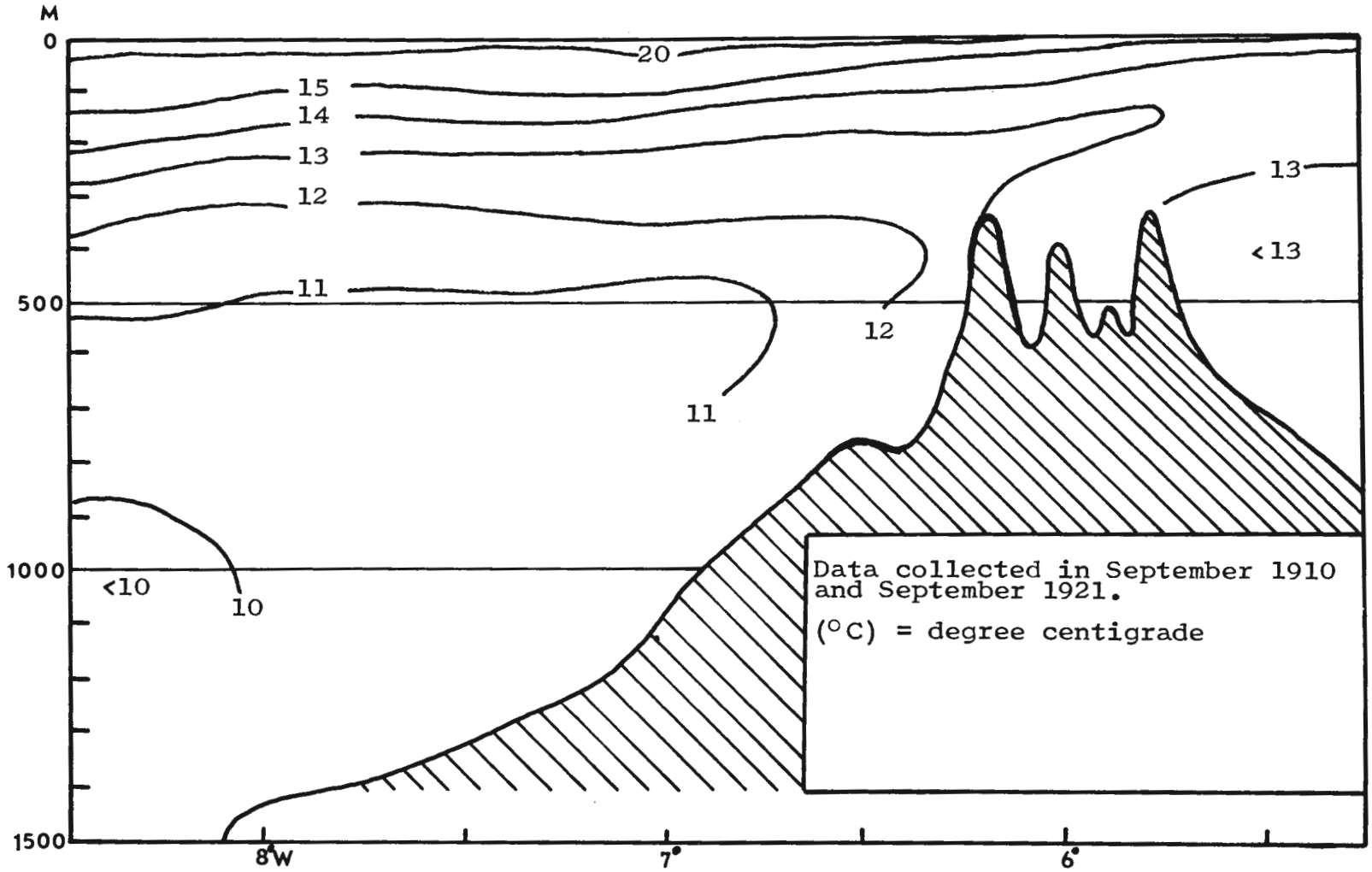


Figure 5b. End-of-summer temperature section. (°C) (after Schott, 1928)

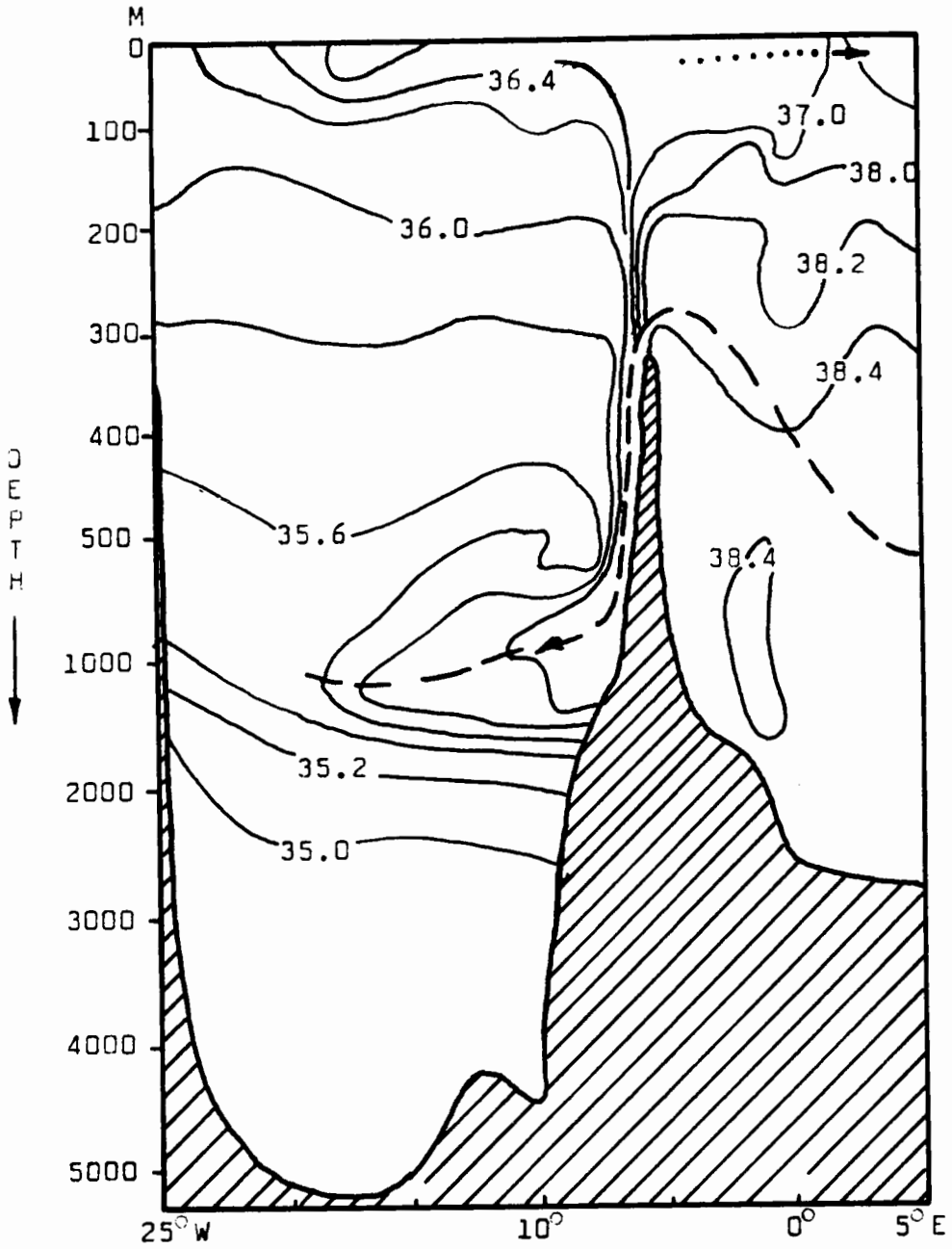


Figure 6. Summer salinity section. (o/oo) (after Lacombe and Tchernia, 1960)

period variations in temperature and salinity. The interface between the two water masses is described as variable in depth and subject to seasonal change or change due to internal waves, tides, wind and atmospheric pressure differential between areas west and east of the Gibraltar Strait. Frassetto believes that the balance of the water economy in the Mediterranean Sea is the basic factor determining the two-way flow through the Strait. This requires an easterly surface flow to replace water loss due to excessive evaporation and the loss over the sill in the westward subsurface current.

Boyum (1965) made an extensive survey of the area west of the Gibraltar Strait in May 1965. He prepared salinity sections across the Strait west of the sill area to show how the Mediterranean water spreads along the bottom. The salinity section, extending north-south along 06° 14' W, Figure 7, shows the interface sloping upward to the north, with high salinity (38.0 o/oo) Mediterranean Water along the bottom. The sloping interface can be attributed to a northward deflection of the deep outflowing water under the influence of the earth's rotation. Additional observations were made west of the Strait, out to 06° 39' West Longitude where almost undiluted Mediterranean Water was found along the bottom extending toward the deep Atlantic Ocean.

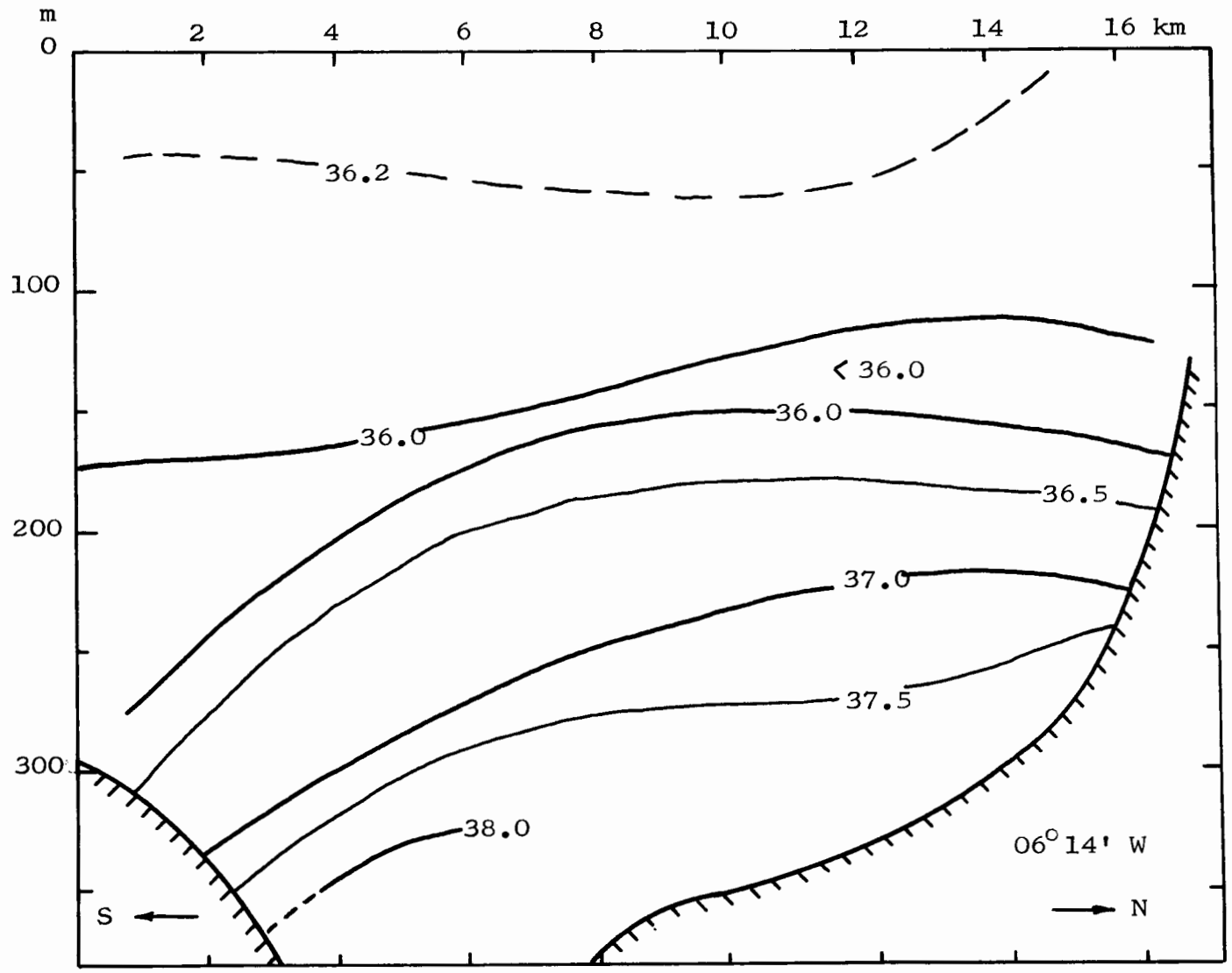


Figure 7. North-south salinity section. (o/oo)
(after Boyum, 1965)

II. THE BATHMETRY OF THE STRAIT OF GIBRALTAR; THE CHARACTERISTICS OF WATER MASSES FLOWING THROUGH THE STRAIT

A. Bathmetry.

The complex morphology of the Gibraltar Strait is depicted in Figure 8, which is a photograph of a relief model constructed by the Instituto Geografico Militare of Florence (Frassetto, 1964). Within the Strait the coastline and the seabed become rougher and more irregular in the western portion. The major sill extends as an arc from Point Al-Boassa (Morocco) to Point Paloma (Spain). A cross-section of this sill, along the minimum depth, is shown in Figure 9. The maximum depth along this sill area approaches 320 meters. A secondary sill, located approximately 12 miles further west, extends from Cape Spartel (Morocco) to Cape Trafalgar (Spain) and has sill depths of 275 and 375 meters which are located, north and south, respectively, of a central rise which extends within 75 meters of the surface.

B. Movement of water masses.

It can be seen that subsurface outflow over the sill will occur only when the densities of the two water masses are different. When water masses of different densities exist across an interface at the same geometric level, a pressure gradient force is established toward the less dense water. For a comparable depth, Mediterranean Water is more dense than Atlantic Water; it therefore must flow out over the sill and follow along the bottom slope.

The pattern of water mass exchange between the Mediterranean Sea and the Atlantic Ocean is shown in Figure 6, which portrays the

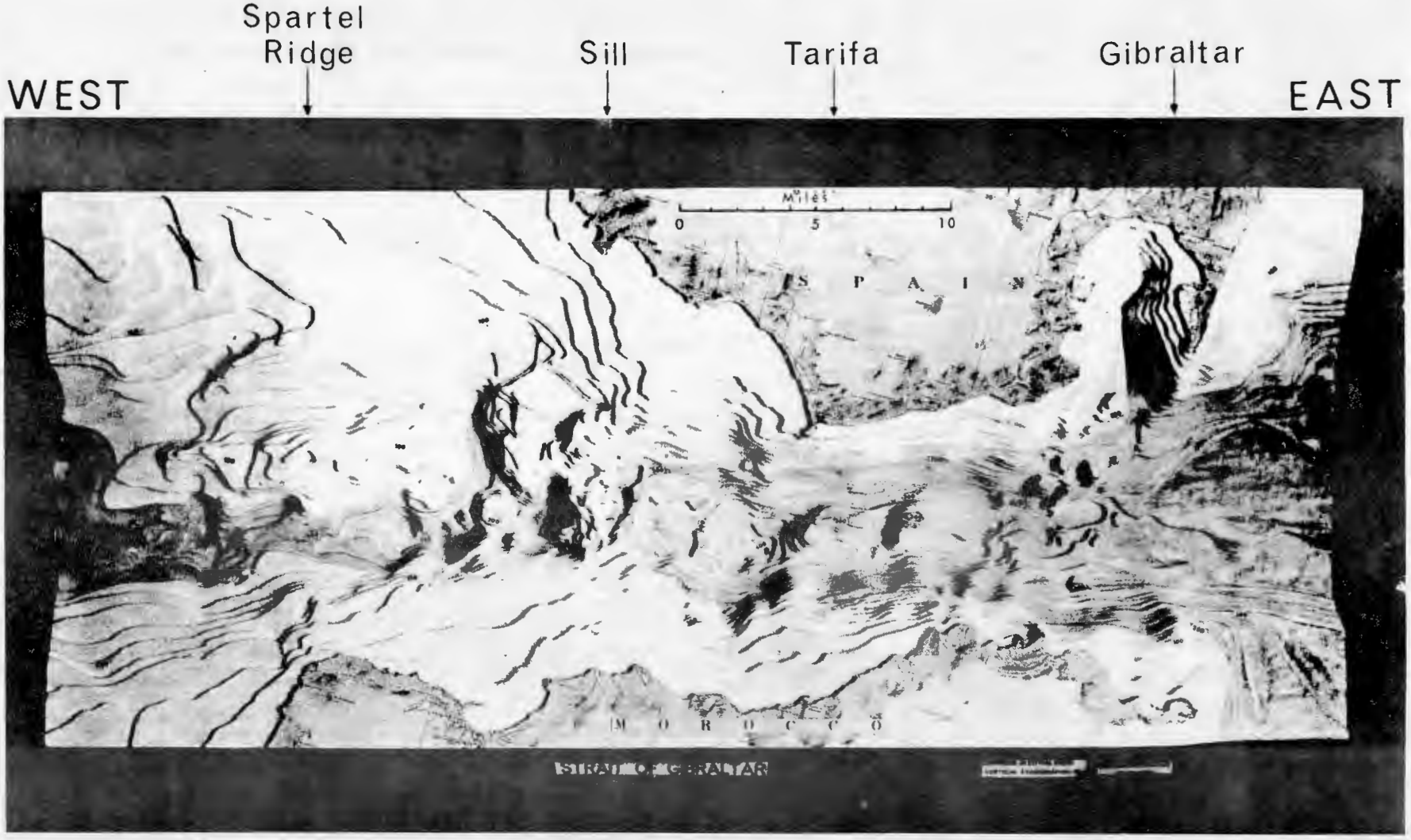


Figure 8. Relief model of the Strait of Gibraltar. The contours are at intervals of 20 fathoms, with a vertical exaggeration of 10:1. The shaded area indicates depths of more than 200 fathoms. (after Frassetto, 1964)

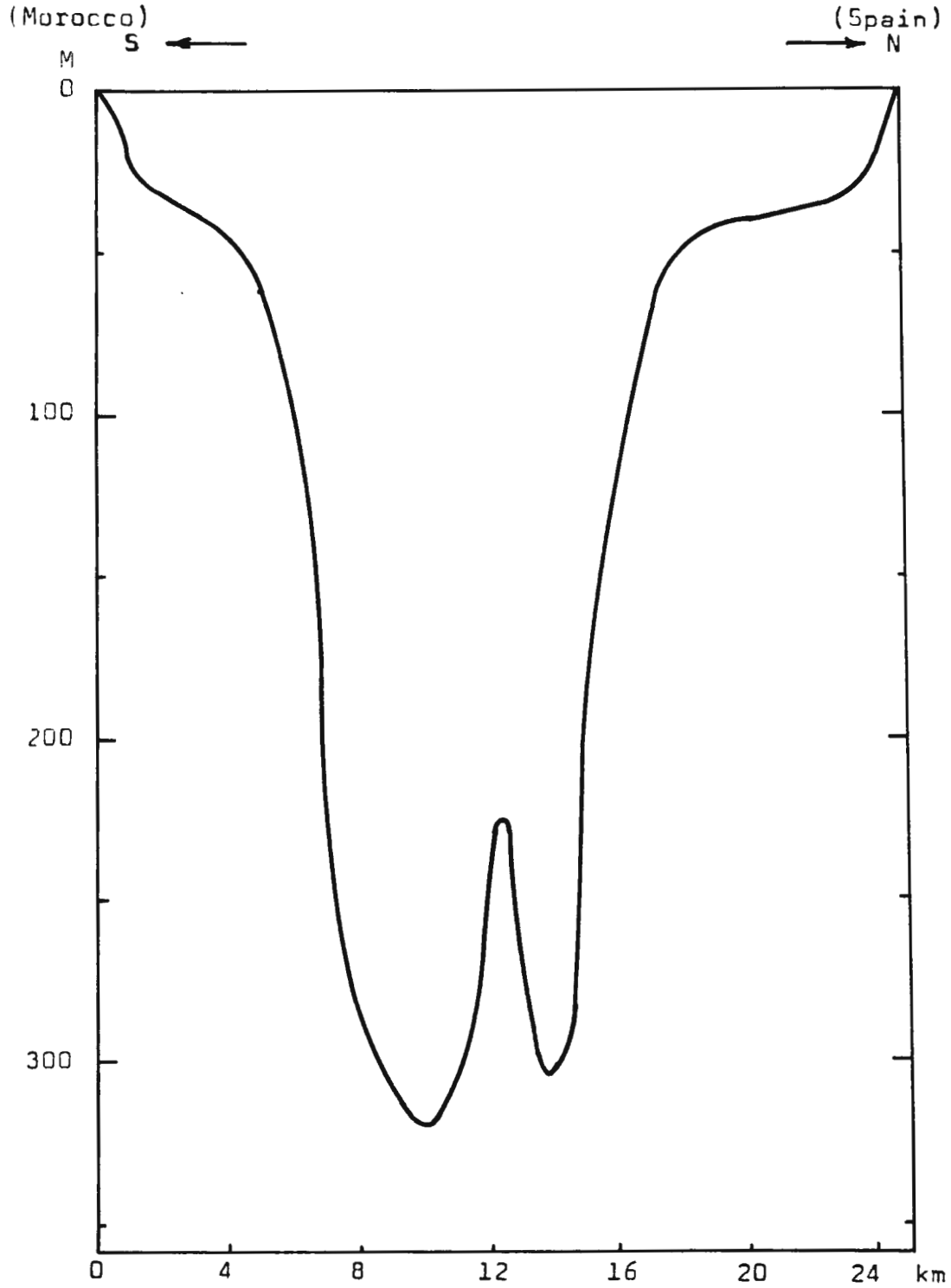


Figure 9. Vertical section across Strait of Gibraltar from Pt. Al-Boassa(Morocco) to Pt. Paloma(Spain).

average salinity conditions for the summer season. Using the "core" method of analysis, as developed by Wust (1935), one can follow the Mediterranean Deep Water as it spills over the sill and spreads into the Atlantic Ocean. Similarly, one can follow the core of the Atlantic Water as it enters through the Strait of Gibraltar to maintain the water balance of the Mediterranean Basin.

Since Nielsen (1912) and Schott (1915) estimated the mass transport through the Strait, there have been numerous other investigations with a resulting wide variation in the estimates. Table 1 shows the results of a number of these calculations based on different sets of data; when known, the season is indicated during which the data were collected.

Table 1. Water balance estimates (10^6 m^3/sec)

Reference	Inflow	Outflow	Season
Nielsen (1912)	1.884	1.791	averaged
Schott (1915)	1.760	1.652	"
Sverdrup et al. (1942)	1.758	1.688	"
Carter (1956)	0.961	0.924	"
Lacombe (1961) measured	1.06 (west of G.)	0.53	summer
Lacombe (1961) "	1.77 (east of G.)	0.75	summer
Lacombe (1961) adopted	1.00	0.96	
Boyum (1963)	west of G.	0.96	spring
Boyum (1965)	west of G.	1.50	spring

Nielsen (1912) and Schott (1915) used the average speed of the upper layer to calculate the total mass inflow. The outflow was calculated using salt budget considerations as described by Sverdrup (1942). Sverdrup's calculations were made using the same data as Schott except Sverdrup assumed a smaller value of salinity for the outflowing water.

Lacombe et al. (1964) made extensive current and hydrographic measurements in the Strait of Gibraltar. Current meters were placed at depths of 10, 50, 100, 200, 300 and 350 meters and continuous profile current measurements were recorded for the semidiurnal tidal period. The average current then was used along with the cross-sectional area to calculate the mass transport through a north-south vertical section across the Strait. The results of numerous calculations showed a large variation in both inflow and outflow. From these Lacombe concluded that a good yearly average for inflow was 1.00×10^6 m^3/sec, but he could not obtain a corresponding reasonable value for the outflow. He reasoned that the difference between inflow and outflow was that of excess evaporation over precipitation and runoff. Based on a balanced water budget and constant water level for the Mediterranean Sea, the outflow was determined to be 0.96×10^6 m^3/sec.

Boyum (1963) observed a correlation in the Gibraltar Strait between salinity and current speed in the water flowing westward over the sill. Using this correlation he was able to convert the observed salinity

section across the mouth of the Strait of Gibraltar into a speed section. This section was then integrated to give a gross outflow of 0.96×10^6 m^3/sec, which agrees with Lacombe's adopted value. However, Boyum (1965) has obtained different results for the outflow as evidenced by his reported value of 1.50×10^6 m^3/sec, based on current measurements west of the sill made by the Helland-Hansen Expedition in May 1965.

Lacombe (1961) used numerous observations of mean sea level and atmospheric pressure to establish that the distribution of atmospheric pressure over the Mediterranean Sea is the probable cause of both the variation in flow through the Strait and the variation of sea level. He attempted to show that an inverse relationship exists between mean sea level and atmospheric pressure along the Mediterranean coast of France. The correlation between these two parameters was not well established for the Algerian coast, indicating that other factors are involved. Lisitzin (1963) has found that the most important factor contributing to the variation of sea level along the coasts is the effect of the force of the wind on the sea surface.

Carter (1956) has made a careful hydrological study of the Mediterranean Basin and calculated the associated evaporation, precipitation and runoff. He determined the net water deficit in the Mediterranean Basin to be 0.038×10^6 m^3/sec. Using this value and taking Sverdrup's salinities for the two layers, he calculated the mass transport through the Strait by use of salt balance considerations for the Mediterranean Basin. Lacombe (1961) reported on Carter's results, Table 2, as a monthly net gain or loss through the Strait.

Table 2. Monthly net mass transport through the Strait of Gibraltar (after Lacombe, 1961) (+ net inflow, - net outflow)

Month	Net flow (10^6 m^3/sec)	Month	Net flow (10^6 m^3/sec)
January	-0.030	July	+0.128
February	-0.048	August	+0.153
March	-0.034	September	+0.121
April	-0.009	October	+0.063
May	+0.032	November	+0.022
June	+0.081	December	-0.017

These results show the maximum net inflow to occur in August and maximum net outflow to occur in February. According to Carter (1956) the maximum net inflow coincides with the season of minimum precipitation and runoff and maximum evaporation, while the maximum net outflow occurs during the season of maximum precipitation and runoff and minimum evaporation.

III. SEASONAL HYDROGRAPHIC SECTIONS

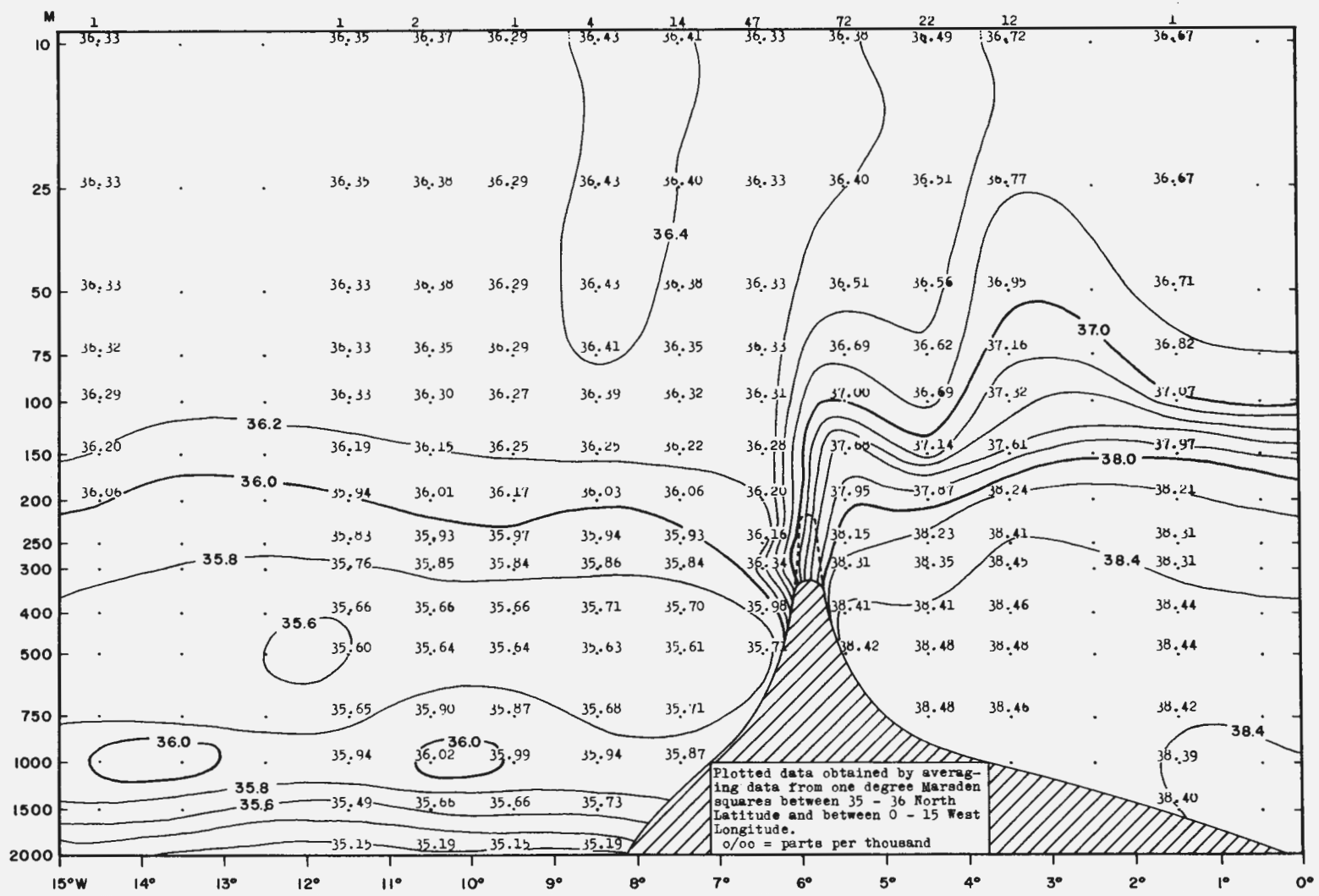
Seasonal averages of salinity, temperature and sigma-t have been computed for each one-degree Marsden square. These data have been plotted and analyzed as shown in succeeding sections (see Figures 10, 12 - 18). The data for each section are plotted to facilitate the reader's evaluation of each analysis. The number of soundings involved in the determination of the plotted data are shown above each data point. In certain areas and seasons data were insufficient to establish realistic averages; no attempt has been made to assign a weighting factor to the individual soundings.

The sill depth indicated on the east-west sections, 320 meters, is the maximum depth across the Al-Boassa Ridge (see Figure 9). The dashed line, 225 meters, indicates the minimum depth between sills along the Al-Boassa Ridge.

A. Vertical (east-west).

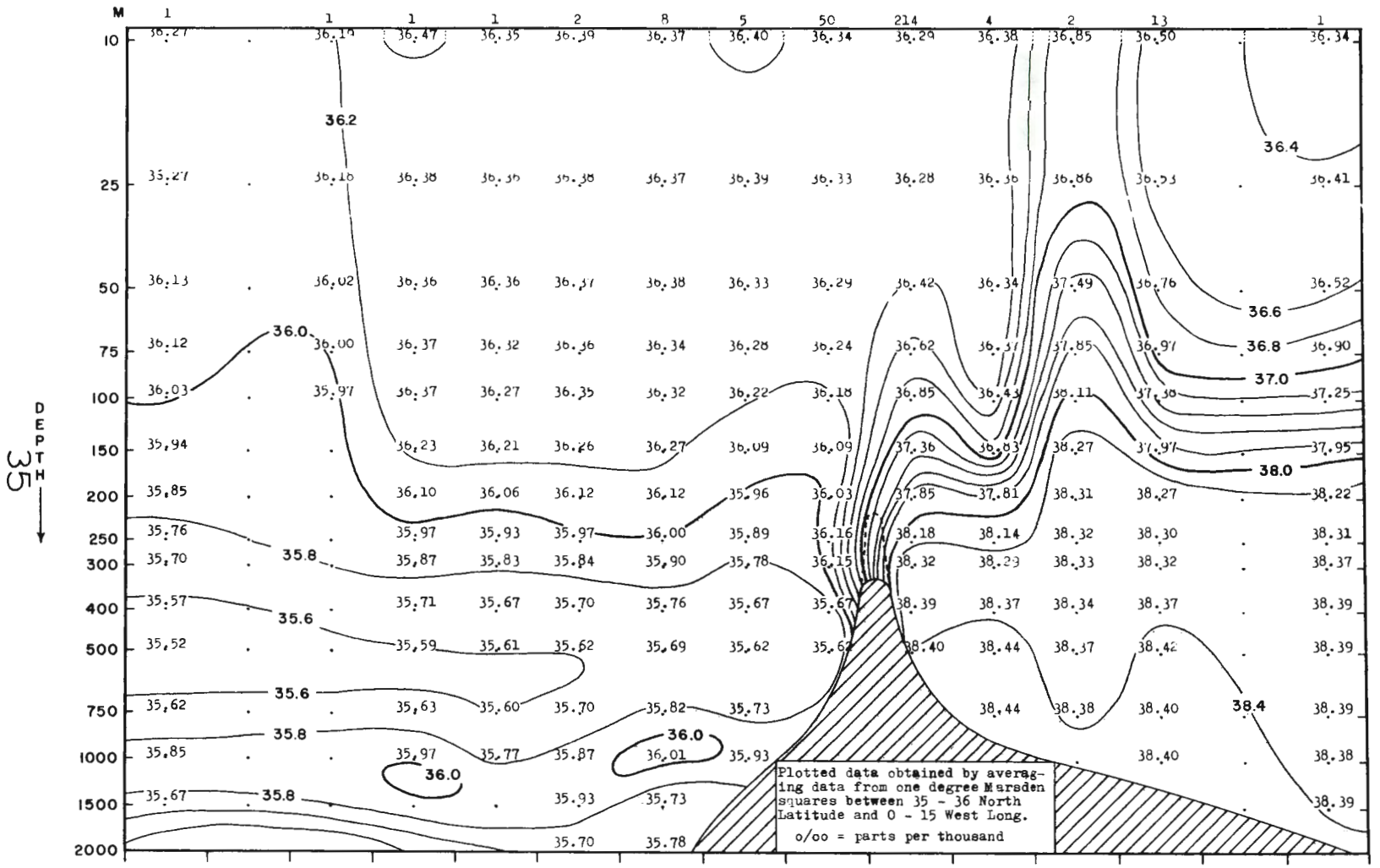
(1) Salinity.

The seasonal distribution of salinity is shown in Figure 10. There are two major features of these sections: (1) spreading of the Mediterranean Water in the Atlantic Ocean; (2) strong salinity gradient above the sill area. Fuglister (1960) shows a May 1959 synoptic salinity section along 36 degrees North Latitude, from North Carolina to the Iberian Peninsula, that compares favorably with the average spring section shown in Figure 10c. Sections for the other seasons were not available for comparison.



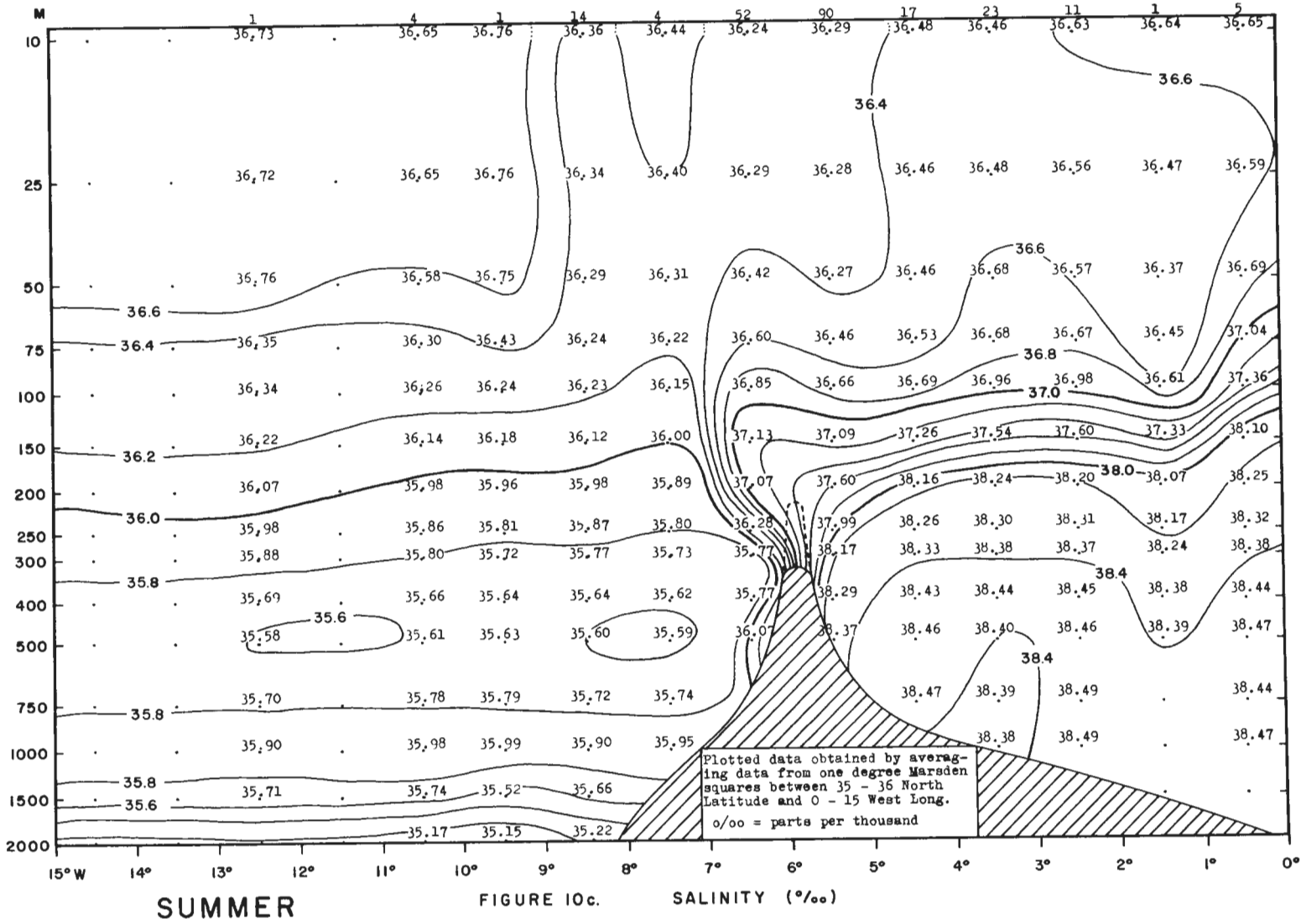
WINTER

FIGURE 10a. SALINITY (‰)



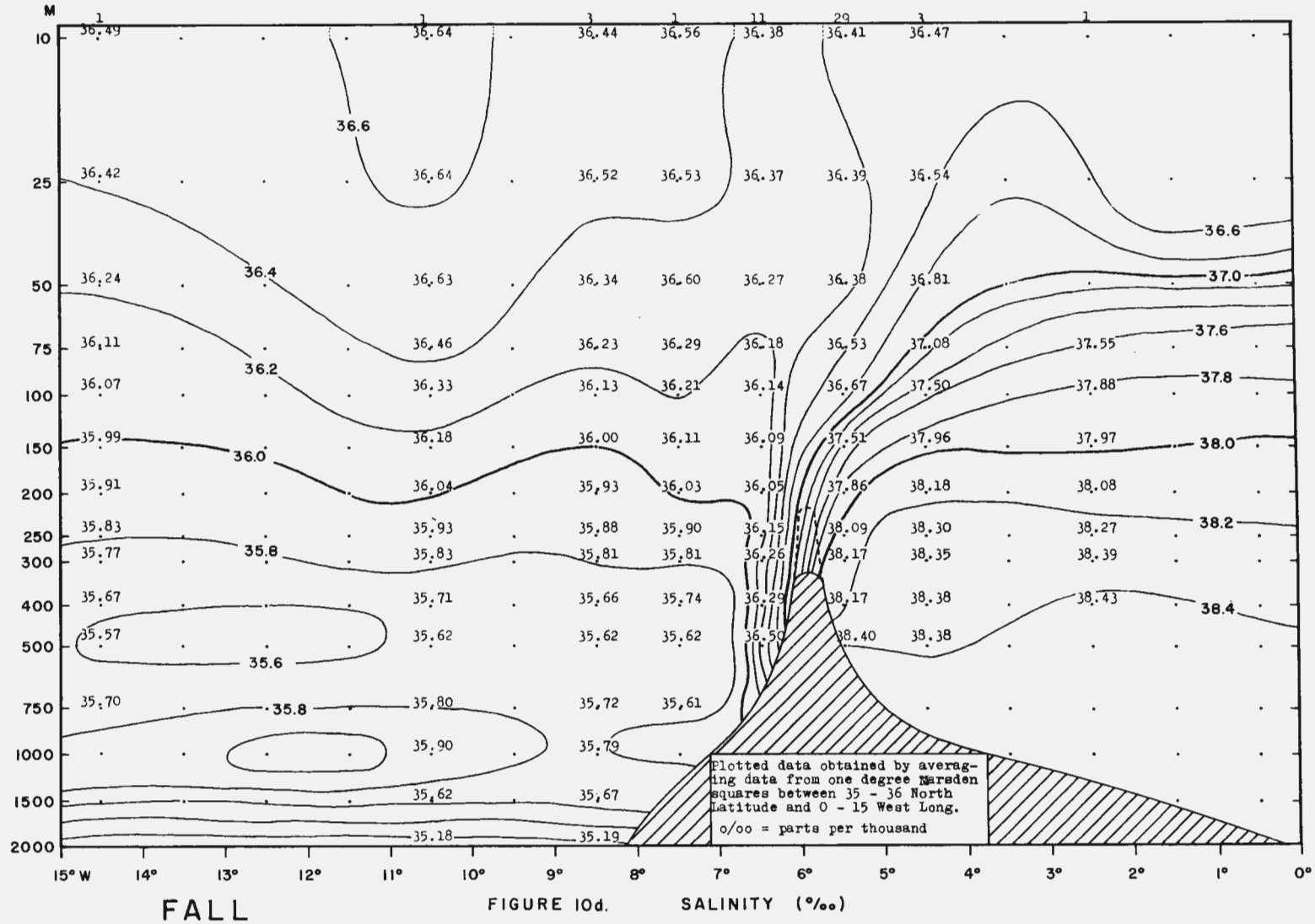
SPRING

FIGURE 10b. SALINITY (°/oo)



SUMMER

FIGURE 10c. SALINITY (°/oo)



FALL

FIGURE 10d. SALINITY (°/oo)

West of the Gibraltar Strait there is a reasonably uniform layer of high salinity water near the 1000-1200 meter level throughout the year, with slightly higher values in winter and spring. The salinity gradient is strong over the sill area and shows as a nearly vertical "wall" throughout the year. The "wall" is maintained by movement of the Atlantic and Mediterranean Water masses, as shown in Figure 11. The system shown on this figure is comparable in many respects to that in the Gulf Stream, with its sloping "Gulf Stream Wall" (see Mazeika, 1968). There are large volumes of water carried into approaches to the Strait area by both Atlantic and Mediterranean currents that do not flow through the Strait, due to the limited dimensions of the layers involved. For a given volume of high density Mediterranean Water arriving in the Strait area, a portion flows over the sill into the Atlantic; the remainder, its salinity decreased by mixing along the interface, subsequently is carried back into the Mediterranean. West of the sill, a portion of the available Atlantic Water flows into the Mediterranean Sea in the surface layers, while the remainder has its salinity increased along the interface. The resultant water has an increased salinity (and density); therefore, it sinks and flows back into the Atlantic Ocean. On the Mediterranean side there is a net loss in salt content through this process while on the Atlantic side there is a net gain in salt. There are indications that horizontal anticyclonic motion exists both east and west of the Strait, as shown in Figure 11, with the motion in the Atlantic being considerable stronger than in the

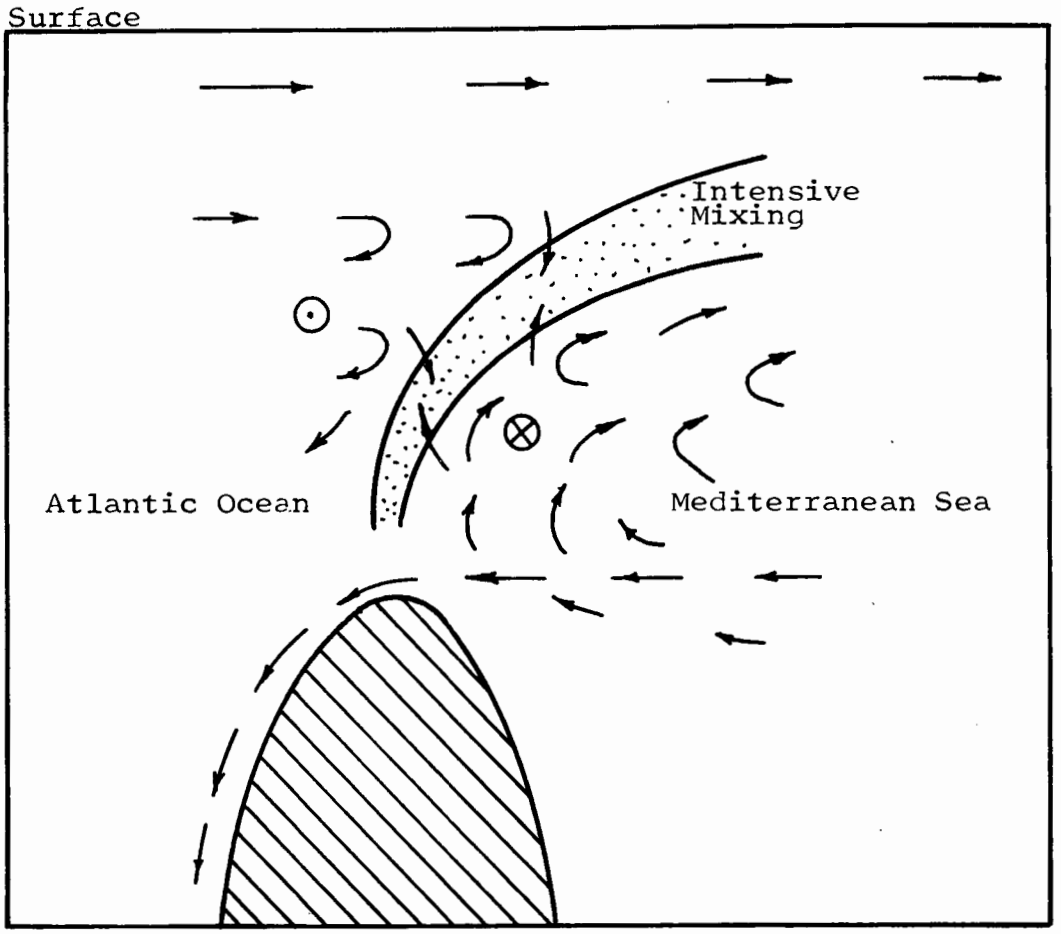


Figure 11. Maintenance of salinity "wall" in Strait of Gibraltar.

Mediterranean Sea. The Spanish Institute of Oceanography (Professor M. Menandiz, personal communication) has observed the anticyclonic circulation east of the Strait; this is suggested in the description given by de Buen (1926) and Schott (1928).

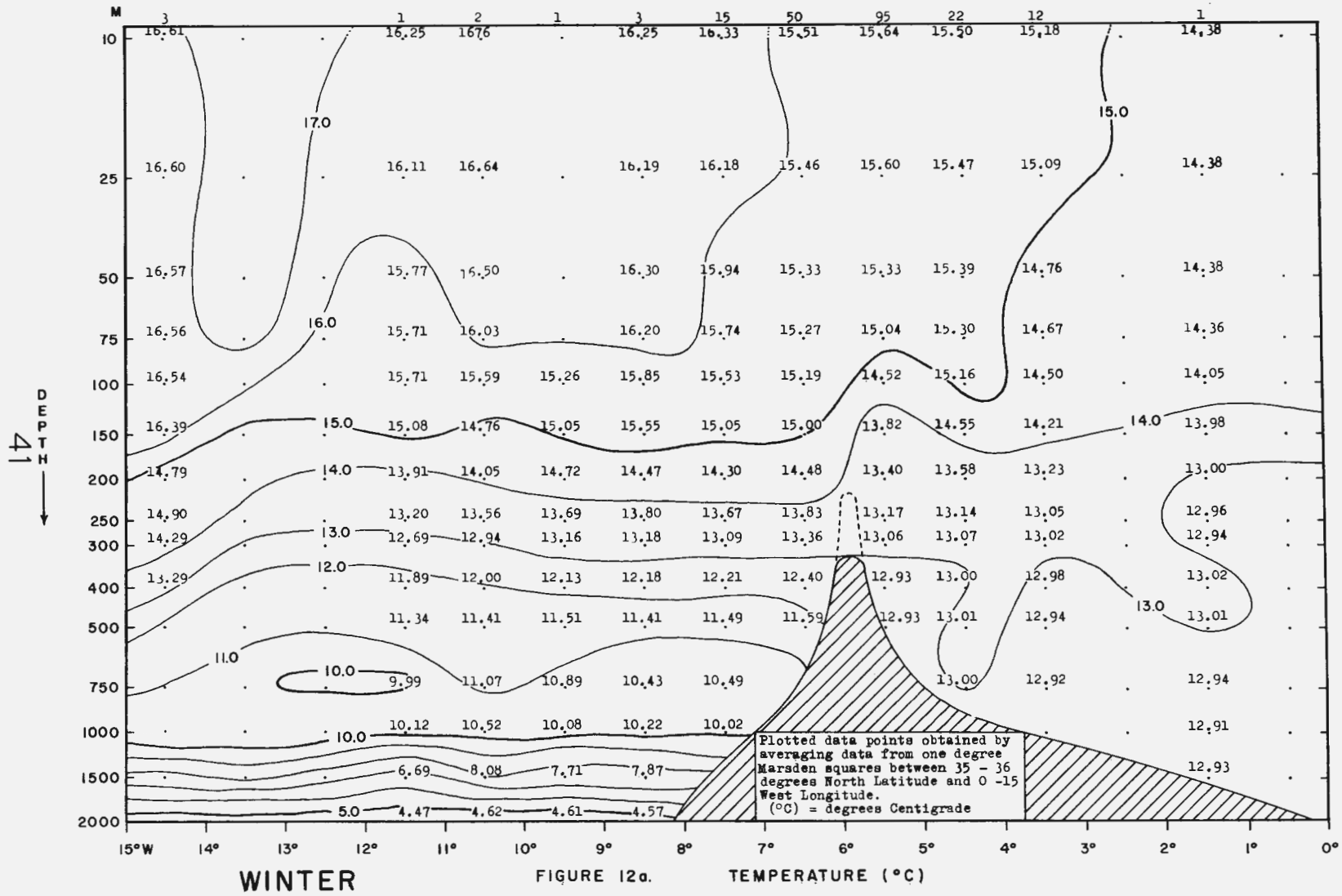
The salinity minimum in the vicinity of 500-700 meters is caused simply by the influence of the highly saline Mediterranean Water flowing beneath the less saline North Atlantic Central Water, which generally decreases in salinity with increasing depth.

(2) Temperature.

The seasonal temperature distribution in the Strait of Gibraltar area is shown in Figure 12. The influence of the Mediterranean Deep Water can be seen east of the sill as the westward moving water is forced upward and mixes with the Atlantic Water. Comparison of the seasonal sections show that temperatures immediately west of the sill are higher in the fall and winter than in spring and summer seasons. West of the Strait the influence of the Mediterranean water is evidenced by increased temperatures in the high salinity region near 1000-1200 meters.

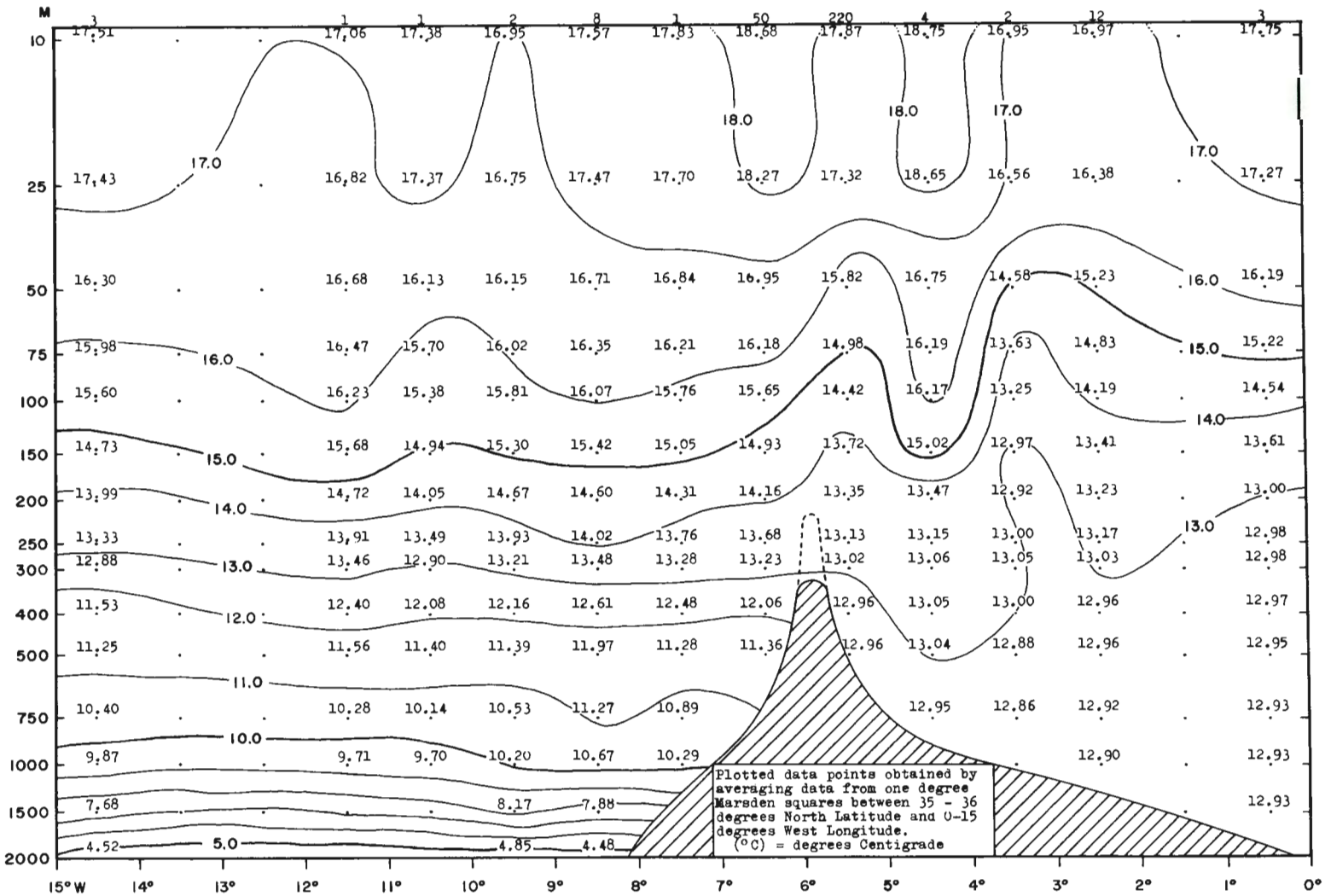
(3) Sigma-t

The main feature of the seasonal sigma-t distribution, Figure 13, is the nearly vertical density "wall" that is in evidence over the sill area throughout the year; however, it is more pronounced and further to the west in the summer season. The reason for this westward bulge of isopycnals in the summer season, Figure 13c, can



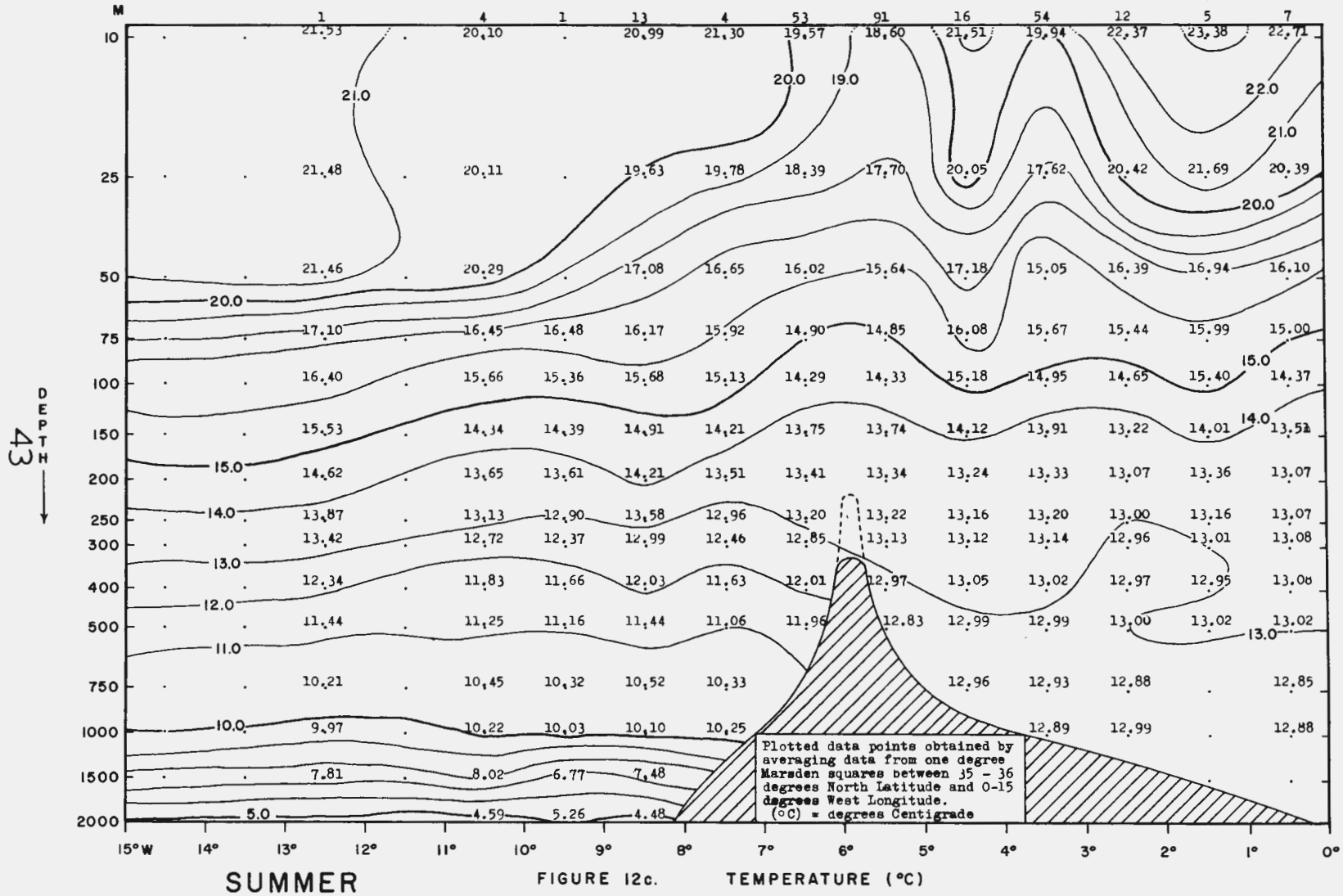
WINTER

FIGURE 12a. TEMPERATURE (°C)



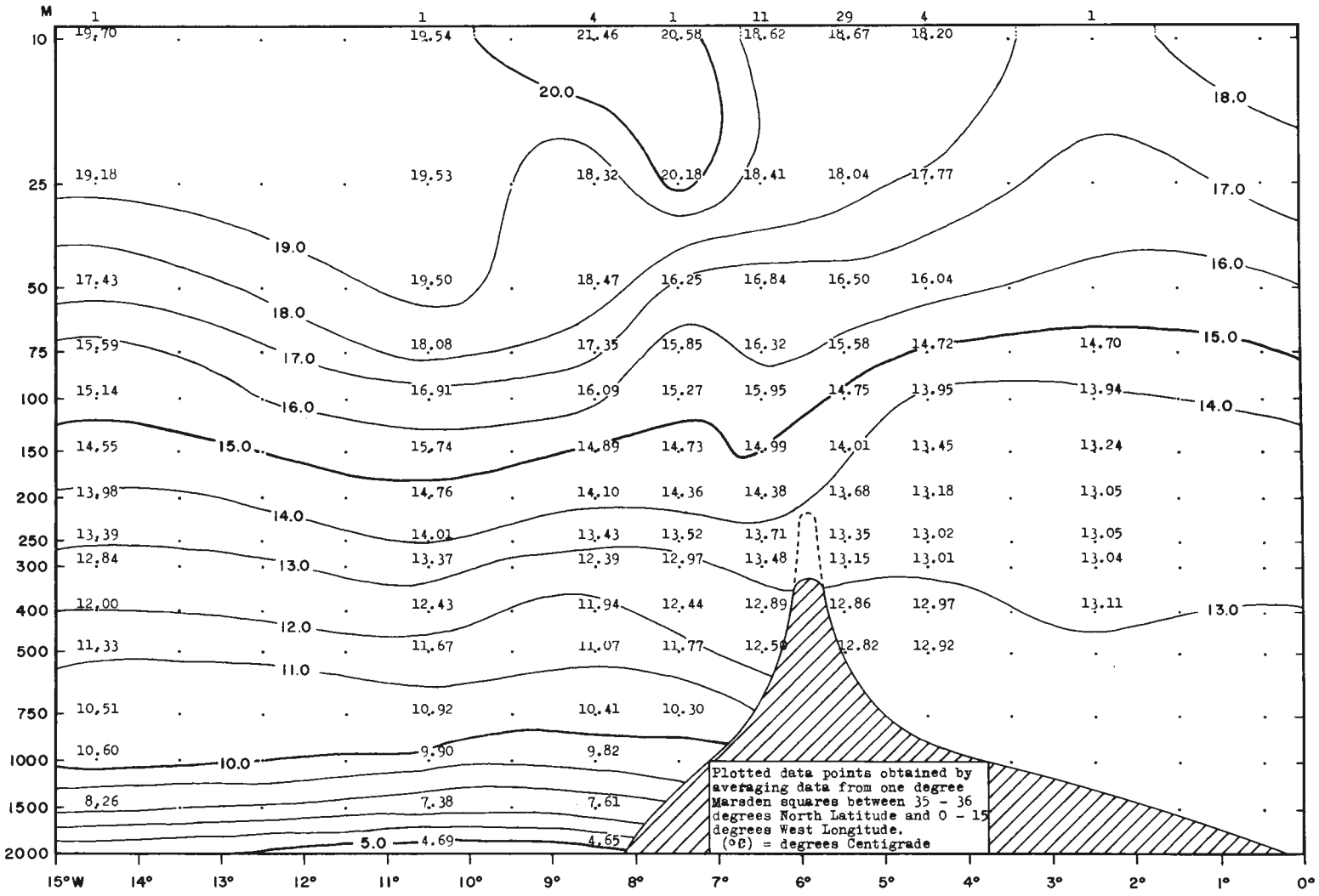
SPRING

FIGURE 12b. TEMPERATURE (°C)



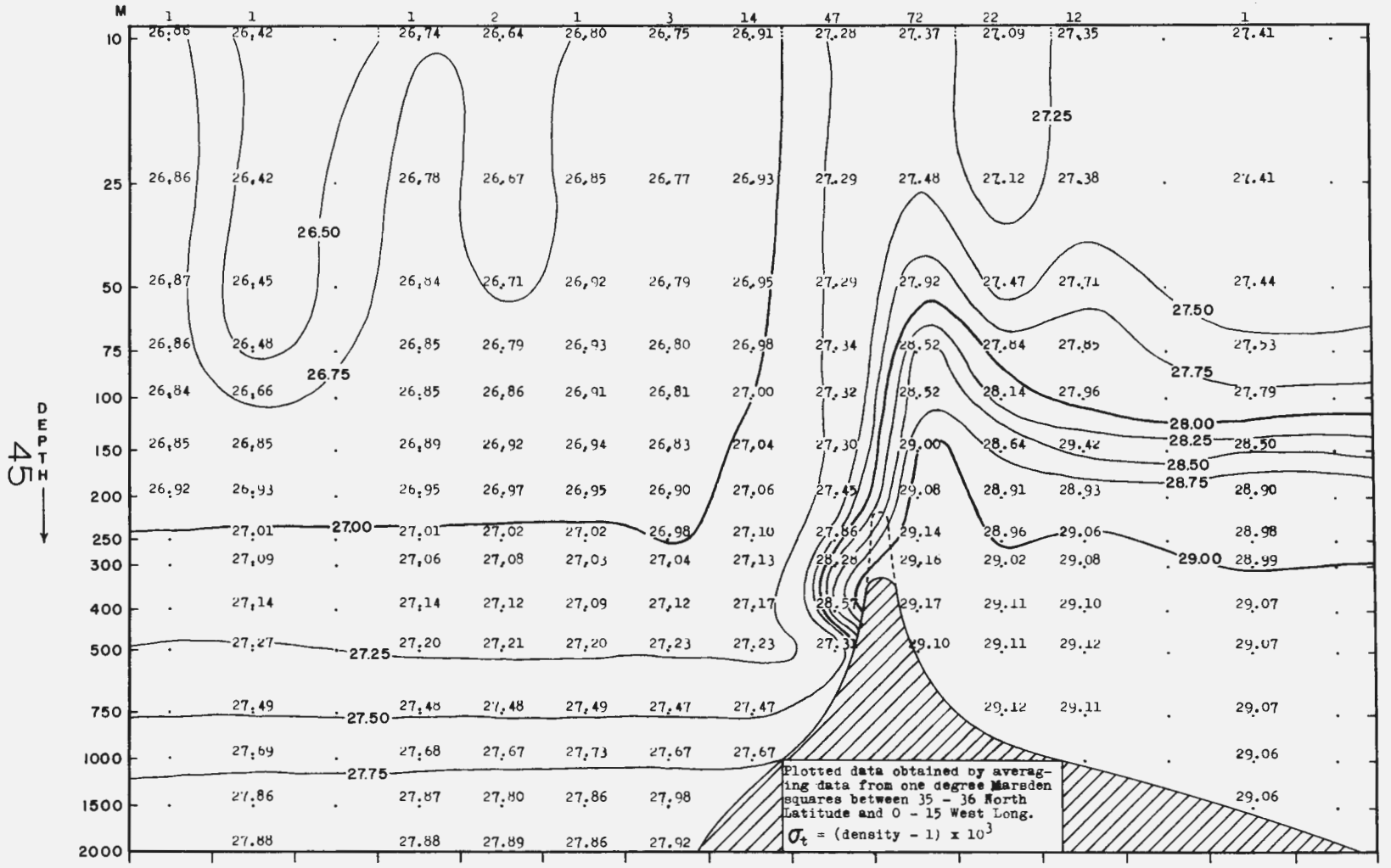
SUMMER

FIGURE 12c. TEMPERATURE (°C)



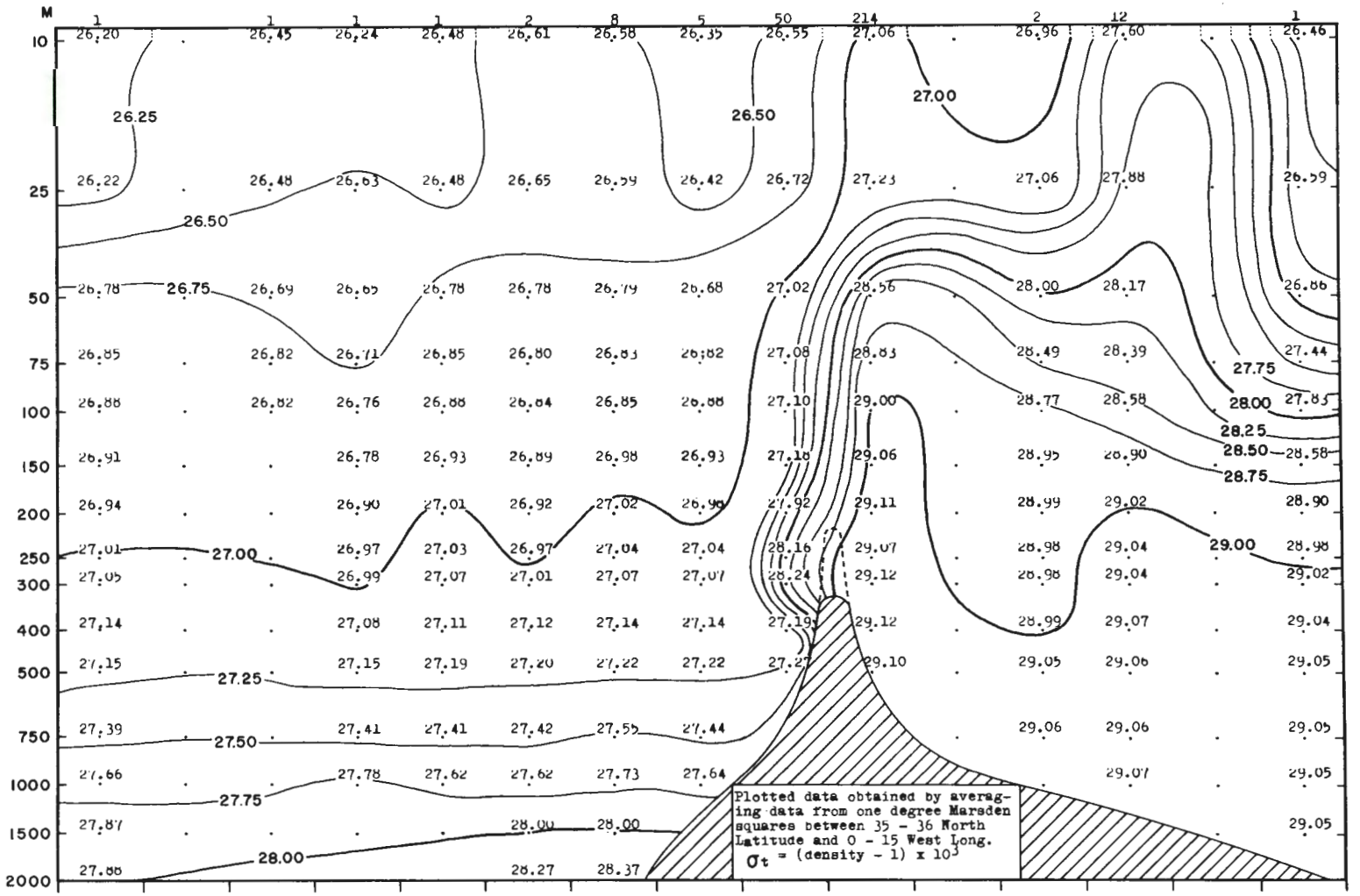
FALL

FIGURE 12d. TEMPERATURE (°C)



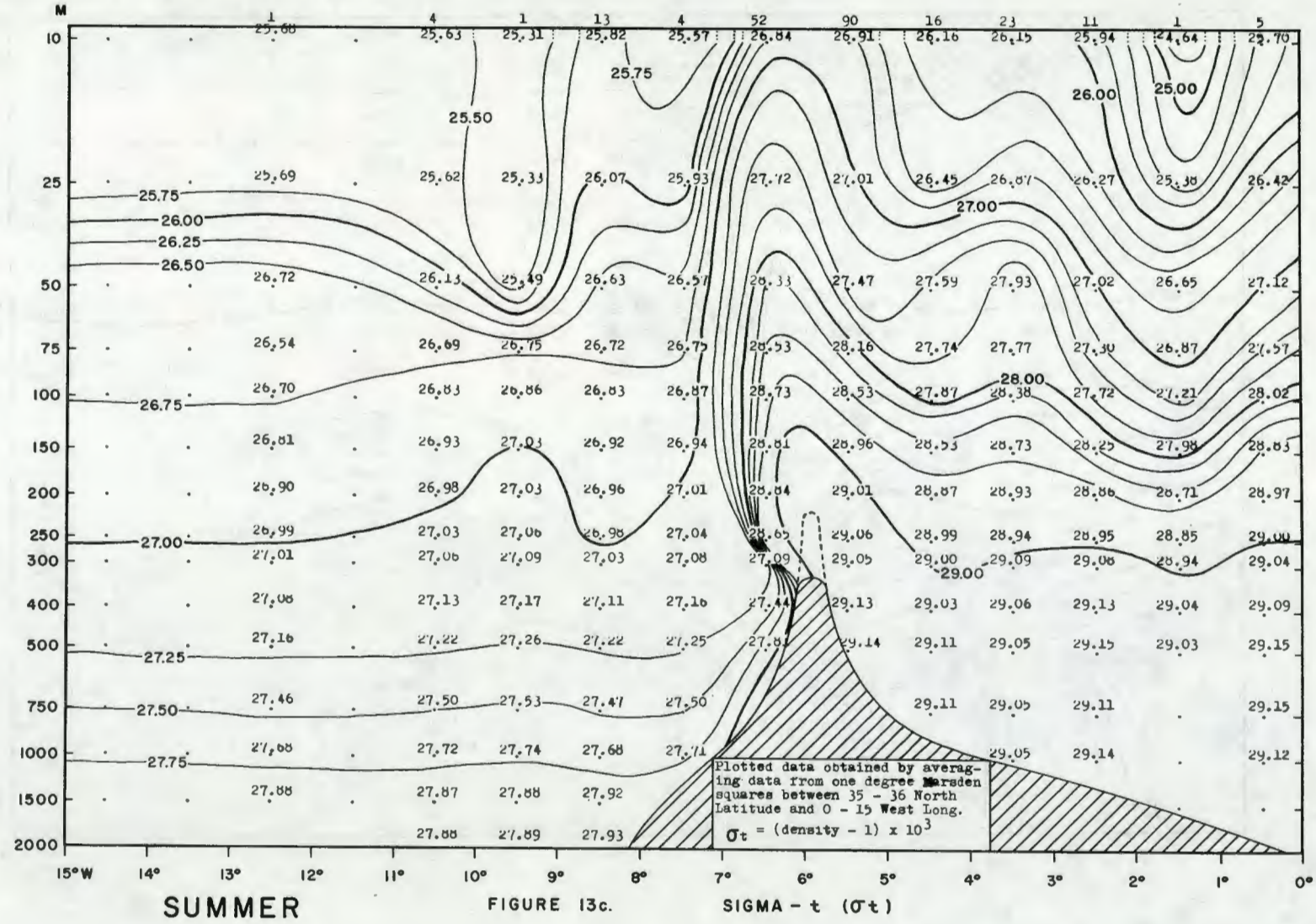
WINTER

FIGURE 13a. SIGMA – t (σt)



SPRING

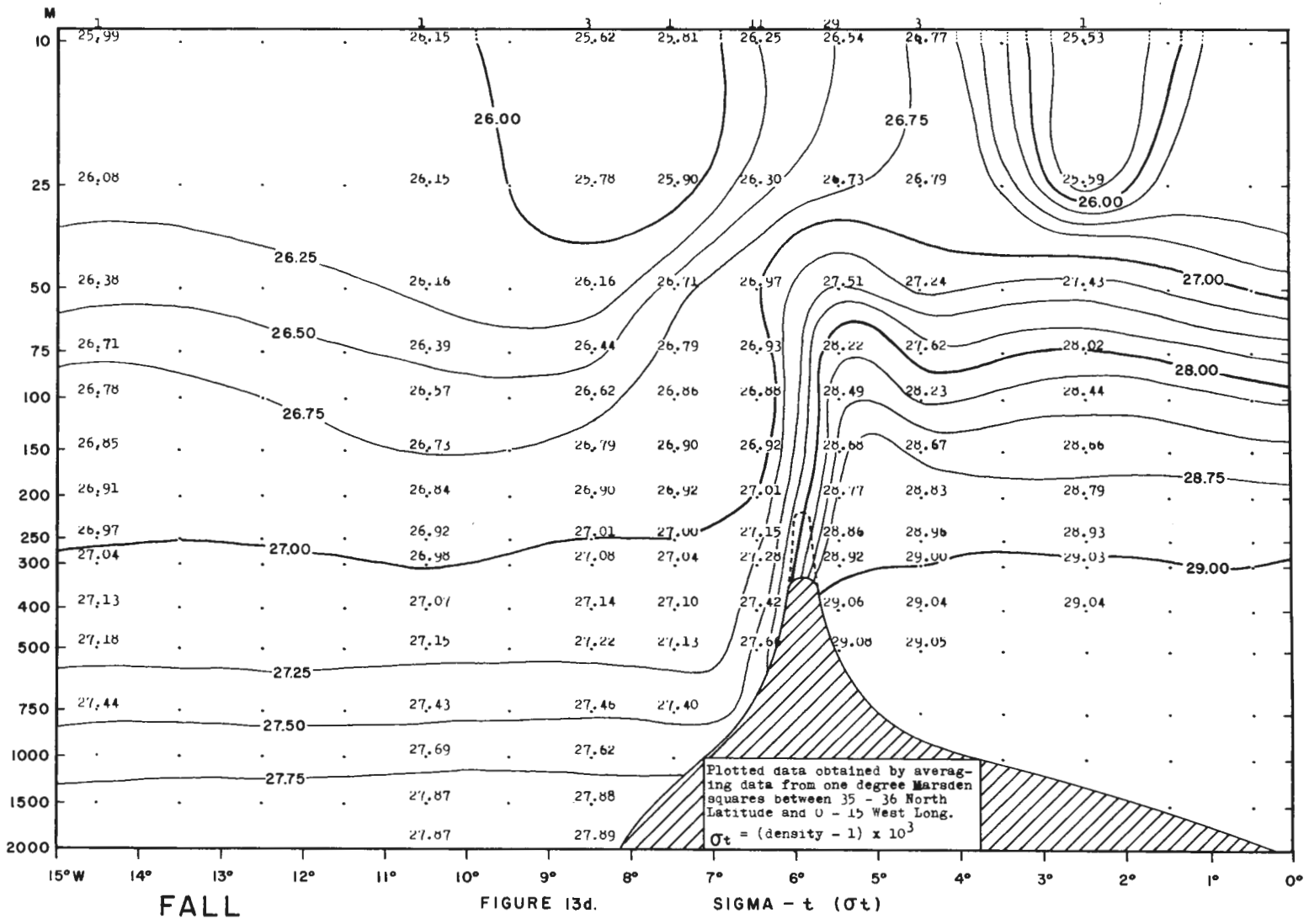
FIGURE 13b. SIGMA - t (σt)



SUMMER

FIGURE 13c.

SIGMA - t (σt)



FALL

FIGURE 13d.

SIGMA - t (σt)

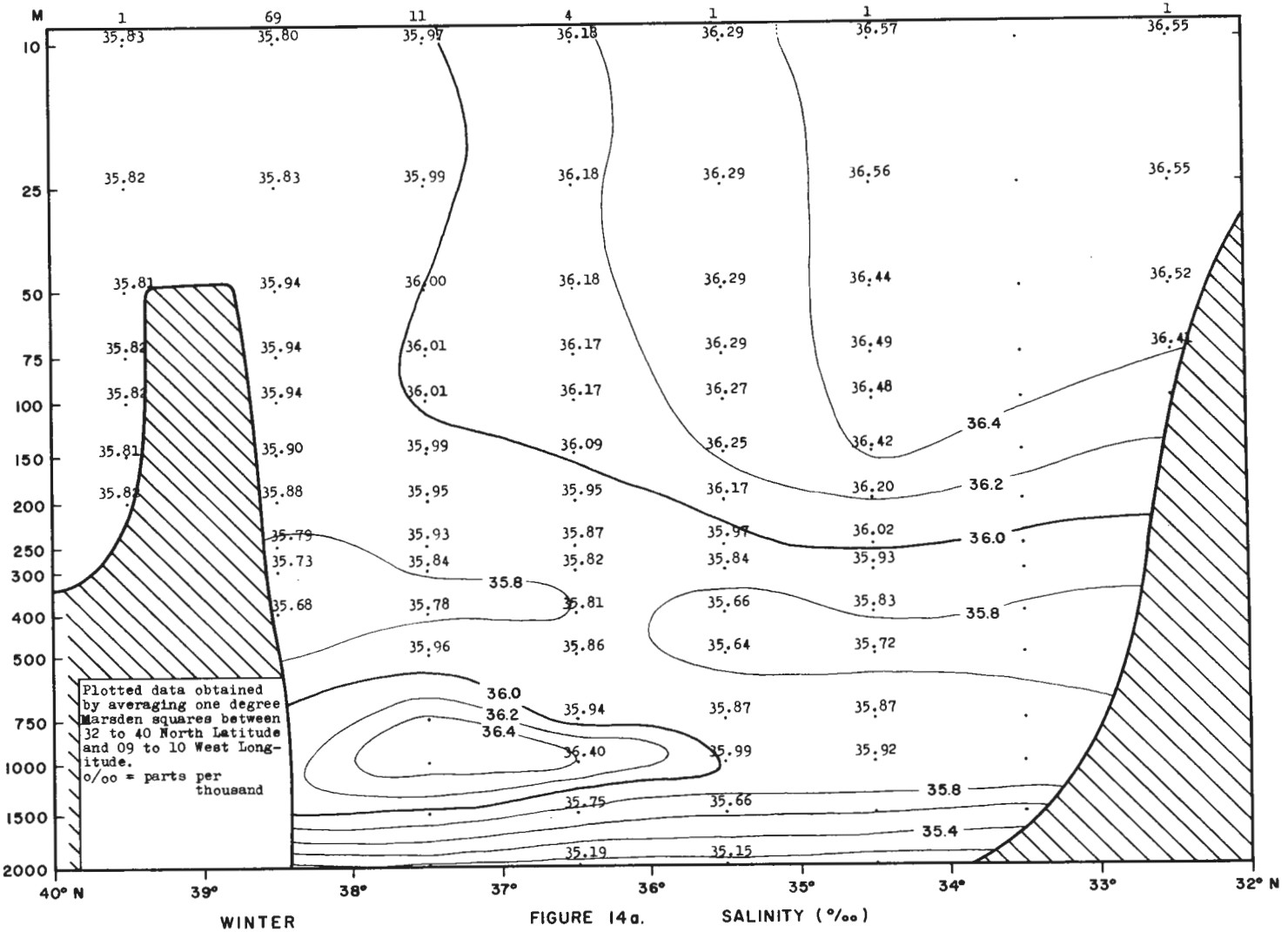
be attributed to the averaging procedure. It has been determined from the individual summer season soundings that several shallow observations (less than 300 meters) were taken during a 12-day period in which the salinities were abnormally high in the near surface layers. When these data were incorporated into an average for the Marsden square area, an "unstable" situation was indicated. This was due to the influence of the shallow, highly saline, observations on the computed averages in the near surface layers (above 300 meters).

According to Sverdrup (1942) the Mediterranean water spreads into the Atlantic Ocean between sigma-t values of 27.60 to 28.80. The averaged sigma-t distribution west of the sill indicates a value of 27.75 is a good average for this modified water as it spreads into the Atlantic Ocean. It is evident that a large volume of water spreads into the Atlantic near the 1000-meter level. Mixing along the interface can result in formation of water of varying density that would spread at various depths into the Atlantic; the variability observed in sigma-t distribution lends support to the suggestion that the spreading outflow does occur with a range of sigma-t values and depths.

B. Vertical (north-south)

(1) Salinity.

The predominant feature of the salinity distribution along a north-south line (9.5^{o} West Longitude) west of the Iberian Peninsula, Figure 14, is the persistence of the high salinity pocket near 1000-1100 meters during all seasons in the vicinity of 37 - 38 degrees North


M
1
69
11
4
1
1
1
10
25
50
75
100
150
200
250
300
400
500
750
1000
1500
2000
DEPTH
35.83
35.80
35.97
36.18
36.29
36.57
36.55
35.82
35.83
35.99
36.18
36.29
36.56
36.55
35.81
35.94
36.00
36.18
36.29
36.44
36.52
35.82
35.94
36.01
36.17
36.29
36.49
35.82
35.94
36.01
36.17
36.27
36.48
35.81
35.90
35.99
36.09
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36.42
35.81
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36.20
35.79
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36.02
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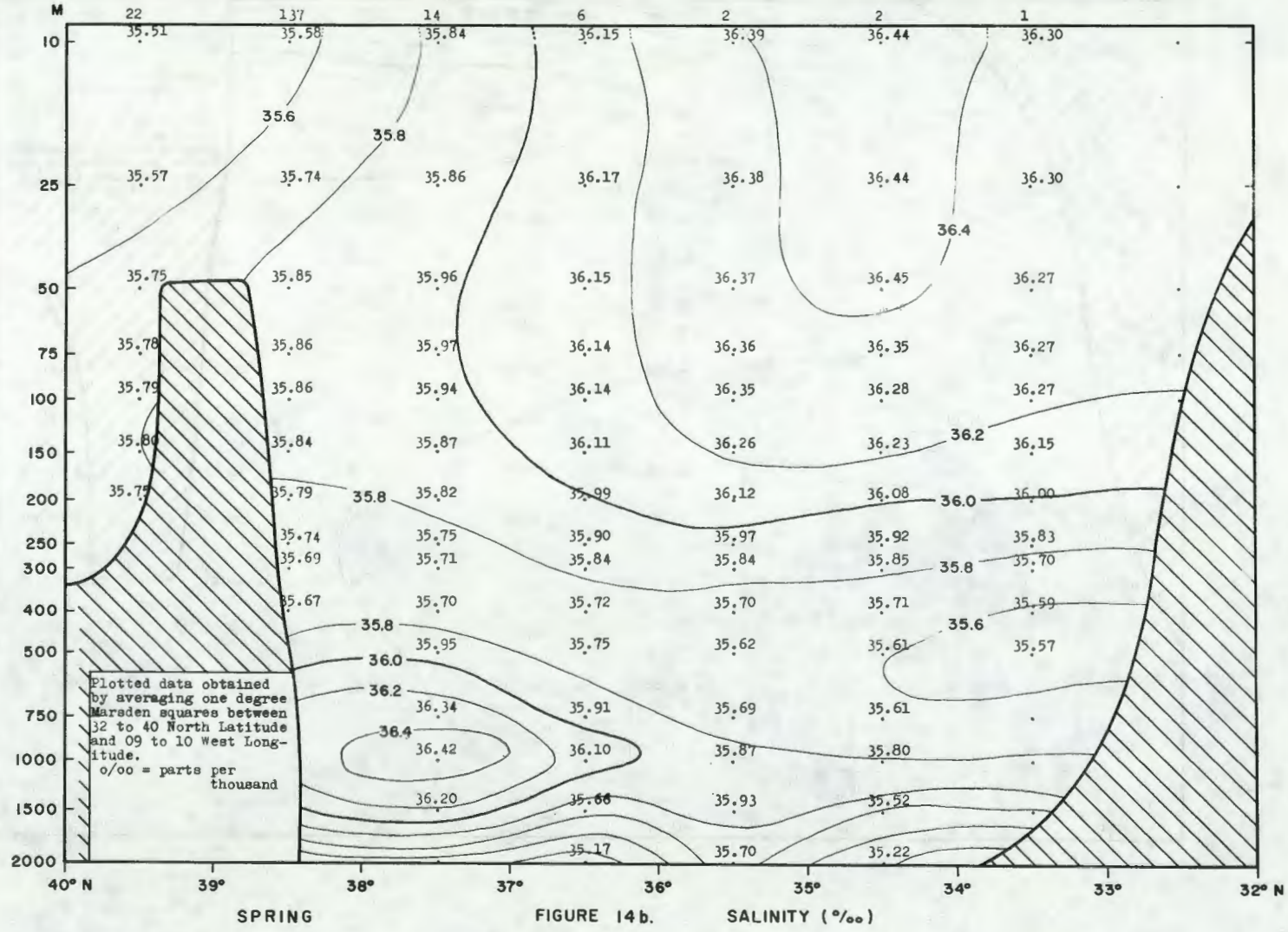
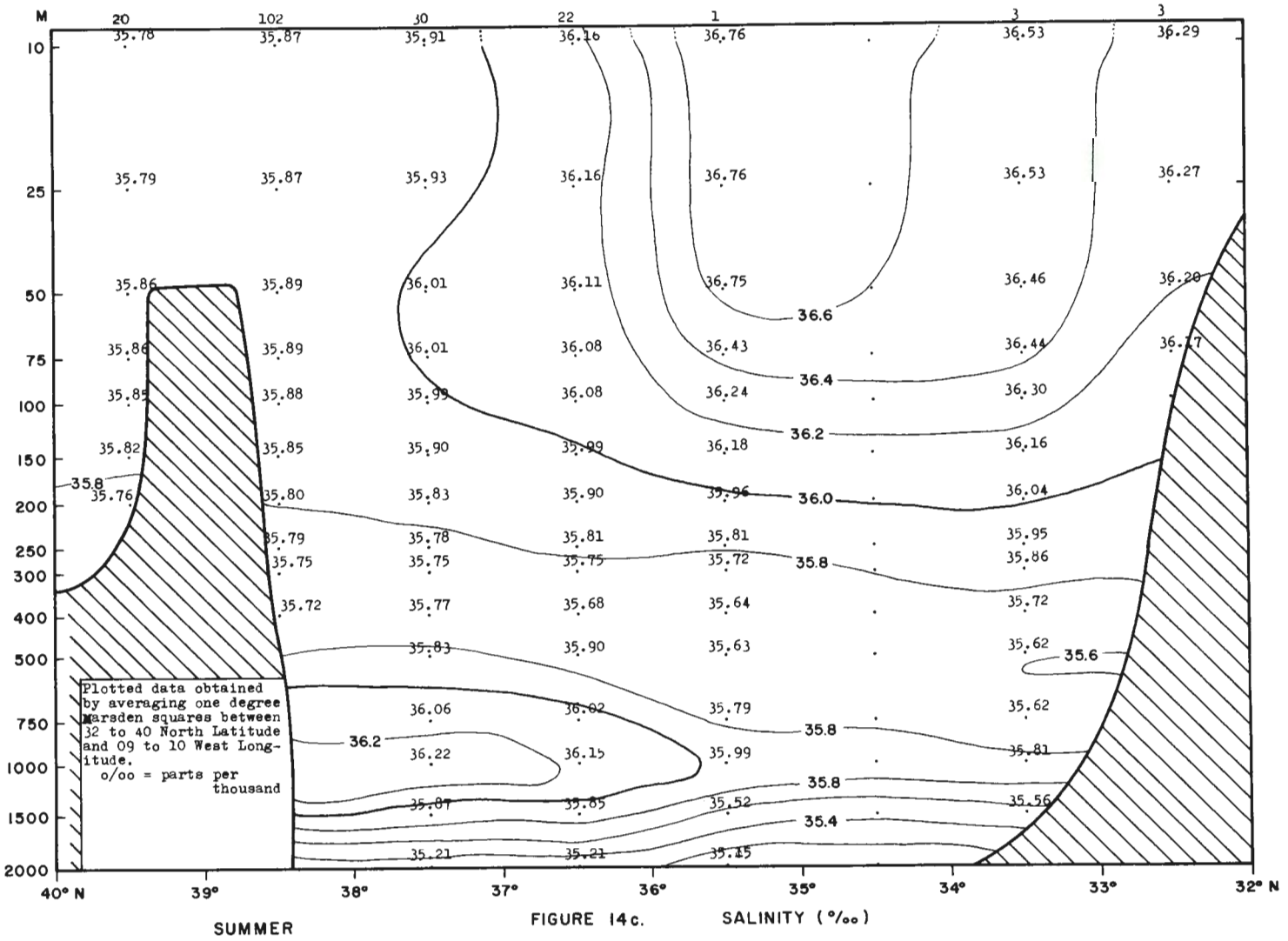
35.81
35.66
35.83
35.96
35.86
35.64
35.72
35.94
35.87
35.87
36.40
35.99
35.92
35.75
35.66
35.19
35.15
36.4
36.2
36.0
35.8
35.8
36.0
36.2
36.4
35.8
35.4
Plotted data obtained by averaging one degree Marsden squares between 32 to 40 North Latitude and 09 to 10 West Longitude.
o/oo = parts per thousand
40° N
39°
38°
37°
36°
35°
34°
33°
32° N
WINTER
SALINITY (°/oo)

FIGURE 14a.

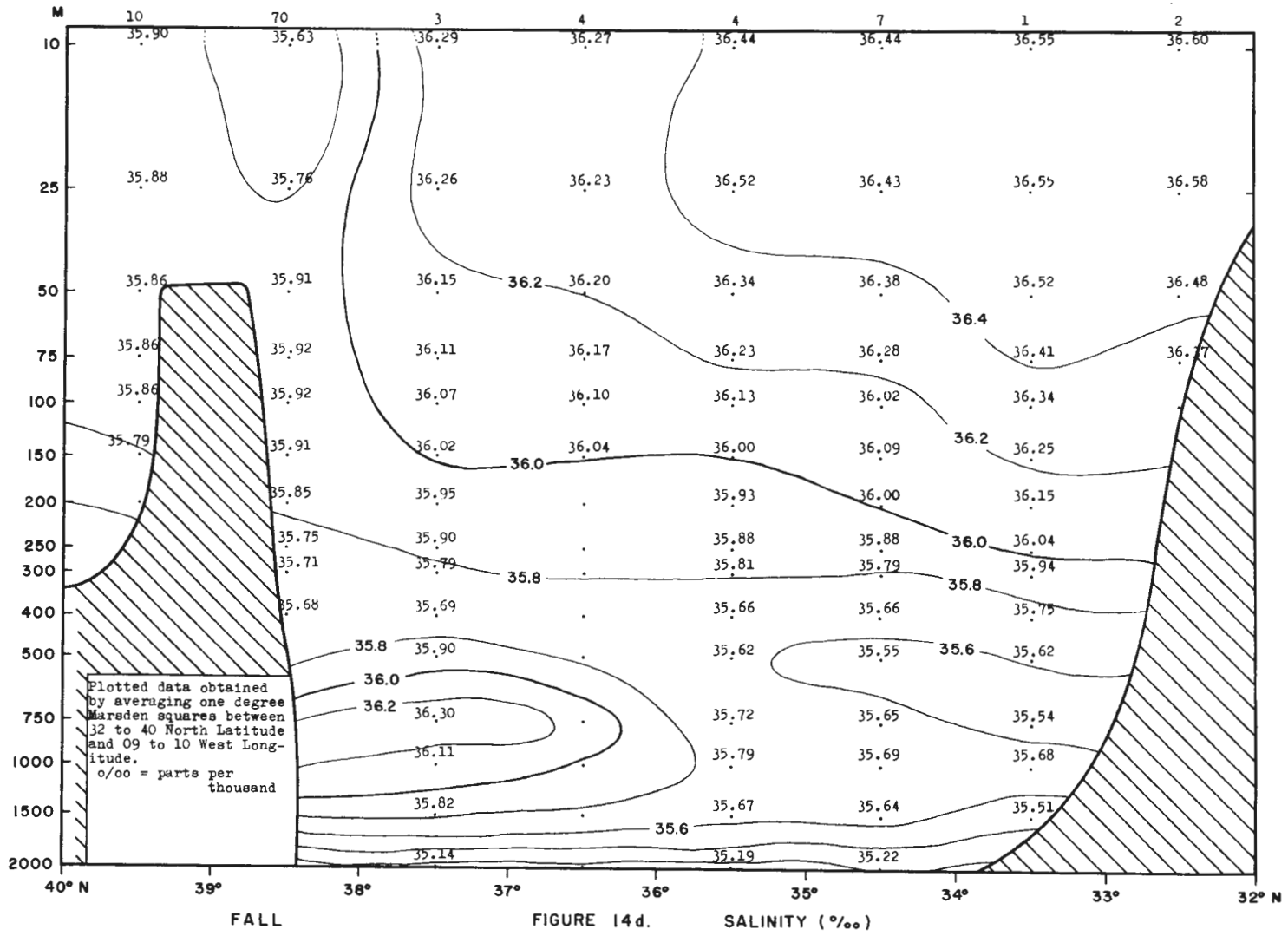


SPRING FIGURE 14b. SALINITY (°/oo)



SUMMER

FIGURE 14c.



FALL FIGURE 14d. SALINITY (°/oo)

Latitude. This salinity maximum is maintained, slightly increased in winter and spring, by the outflow of Mediterranean Water along the coast of the Iberian Peninsula.

C. Horizontal

(1) Sea level pressure and surface winds.

The seasonal distribution of sea level pressure and surface winds are shown in Figure 15 (H.O. 134 and Climatological and Oceanographic Atlas for Mariners). The frequency of occurrence of wind direction is shown for Lisbon, Gibraltar and ocean areas for which data were available.

The pattern of the isobars, Figure 15, indicates the predominant wind to be from the north quadrant throughout the year. This is supported by the wind data, except in the Strait area where the topography influences both wind speed and direction. The decreased pressure gradient during fall and winter is consistent with the diminished intensity and southwestward displacement of the Azores high pressure cell and with the absence or weakened condition of the thermal low pressure system over the Sahara Desert. In the spring and summer the pressure gradient is distinctly increased to about twice that of fall and winter, and the isobars are orientated more toward the northeast-southwest direction.

Considering mass transport of water due to wind action, it is clear that the basic wind regime of spring and summer results in westerly flow at the surface or at least it acts to decrease the existing easterly current in the surface layers.

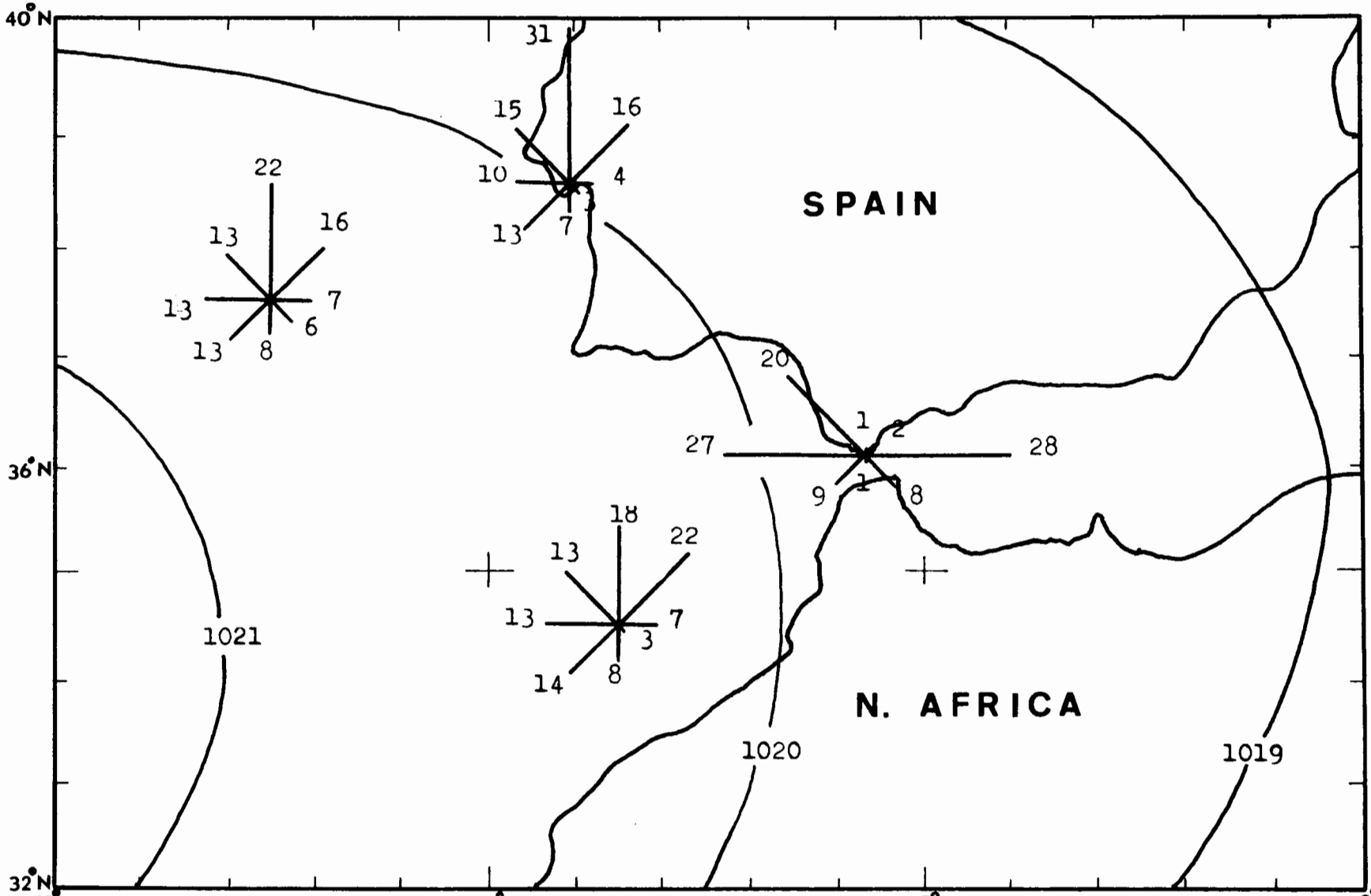


Figure 15a. Sea level pressure and surface winds. (millibars, %)

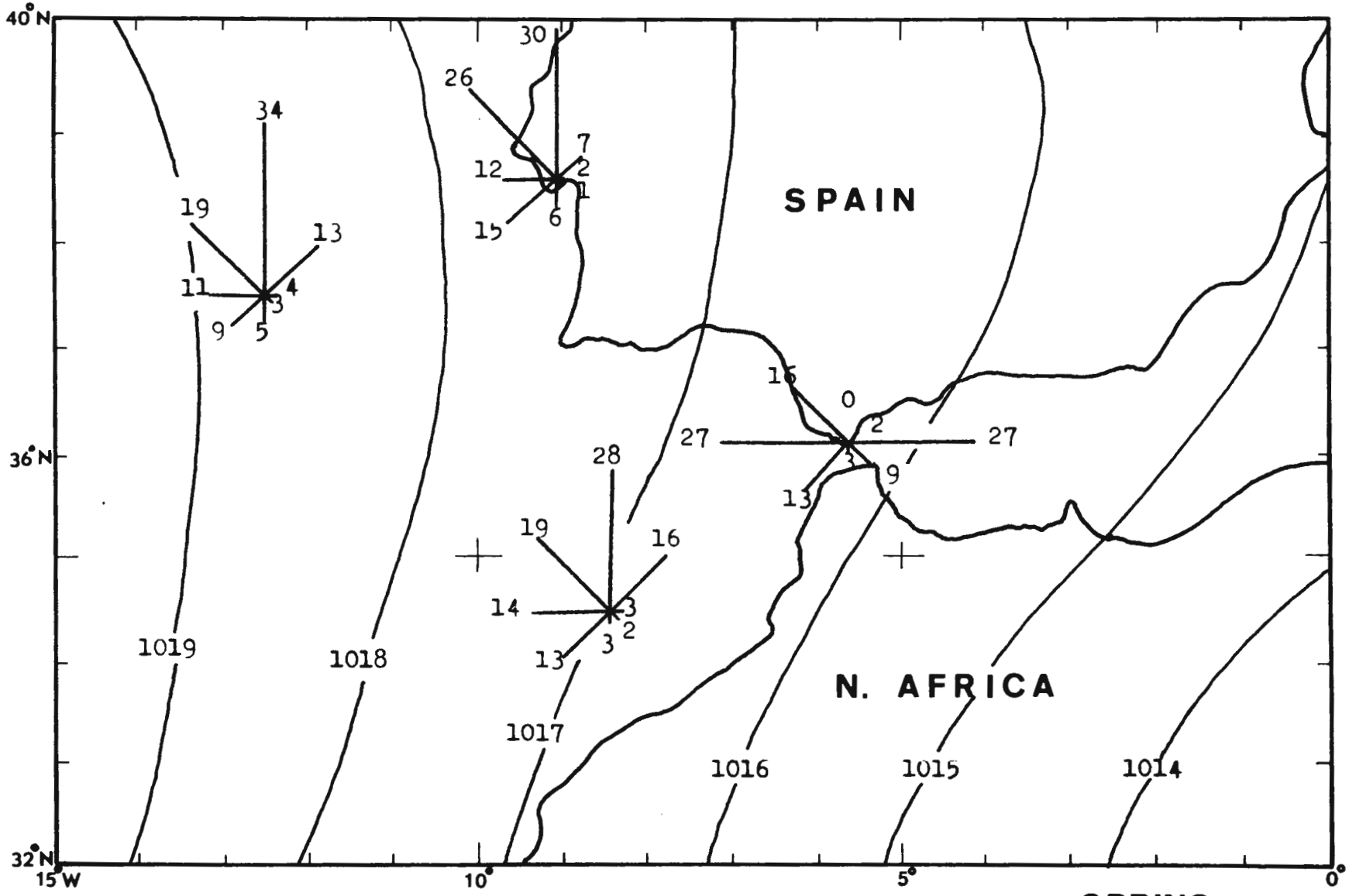


Figure 15b. Sea level pressure and surface winds. (millibars, %)

SPRING

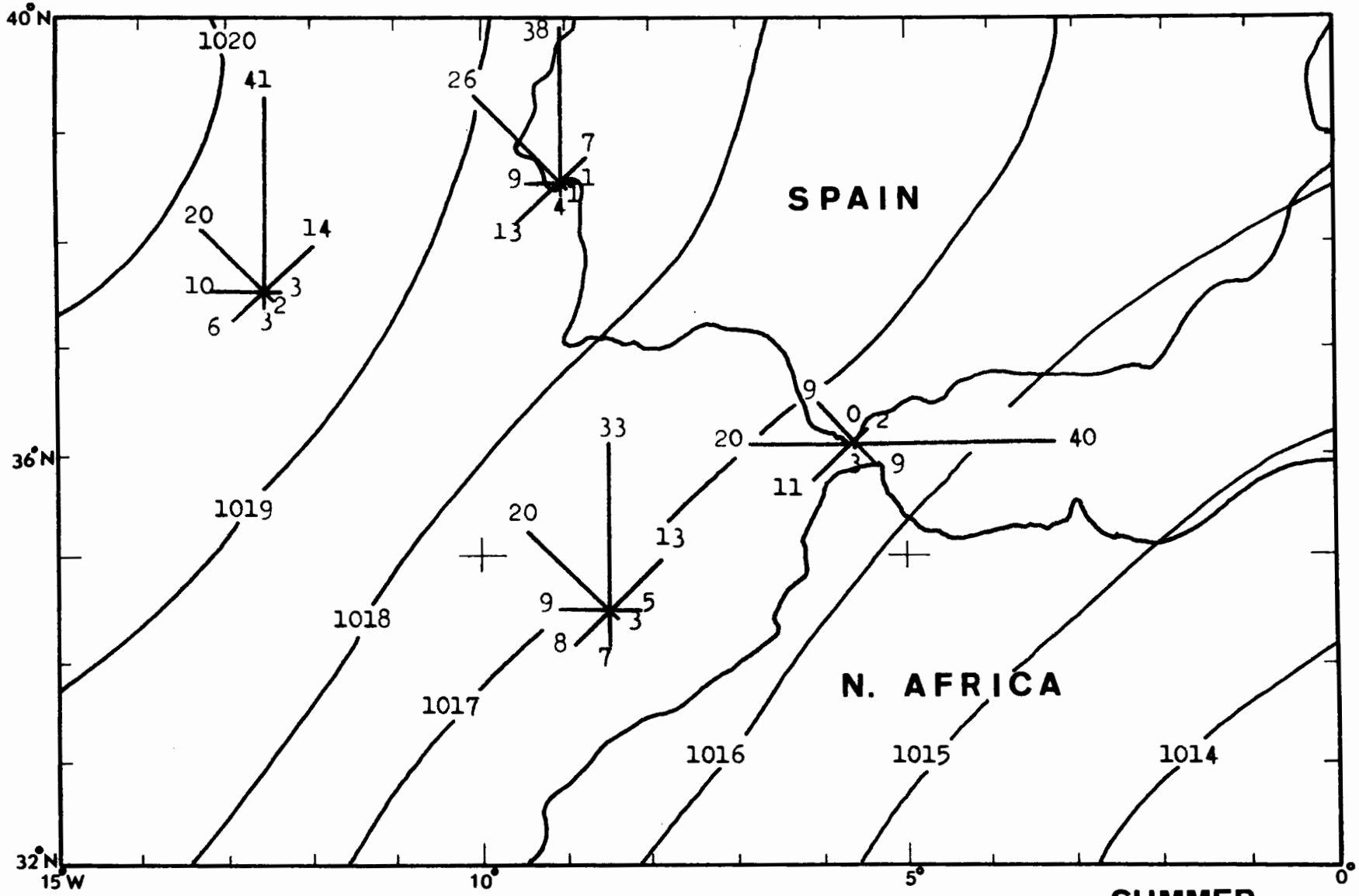


Figure 15c. Sea level pressure and surface winds. (millibars, %)

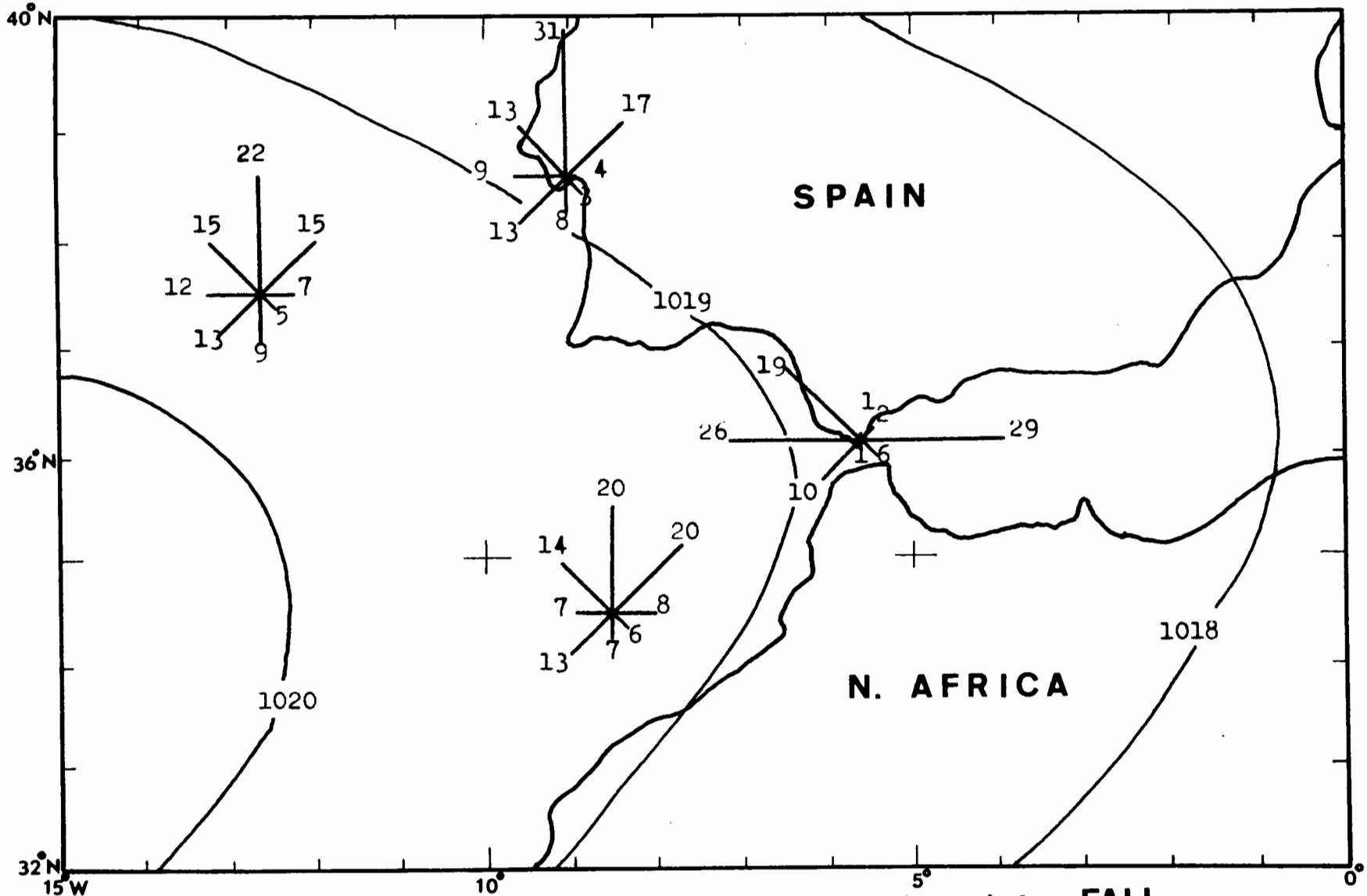


Figure 15d. Sea level pressure and surface winds. **FALL**
(millibars, %)

(2) Surface salinity.

The seasonal surface salinity of the Atlantic Water entering the Mediterranean Sea through the Gibraltar Strait is near 36.3 o/oo throughout the year, as shown by Figure 16. East of the Strait, surface salinity increases with increasing distance from the entrance, due to mixing with the Mediterranean Water. Isohalines were not drawn for the Strait area and Mediterranean Sea because of the high salinity gradient and limited number of data points. Along the coast of Morocco a salinity minimum is in evidence throughout the year although it is much more pronounced in the summer season. West of the sill, near 10 degrees West Longitude, a salinity maximum appears throughout the year, with a maximum value of 36.8 o/oo occurring in the summer. This maximum appears to be related to the wind regime of this region illustrated in Figure 15. The seasonal average sea level pressure and surface wind patterns clearly indicate the increased pressure gradient and surface winds from the north for the spring and summer seasons. The salinity maximum and period of maximum "upwelling" are related, since the increased surface winds in spring and summer result in excessive evaporation (higher salinities) and at the same time deflect the surface water away from the coast with the resultant "upwelling" of less saline water. It is concluded that "upwelling" is a maximum along the Moroccan Coast in the summer, but it probably occurs intermittently throughout the year depending on the synoptic situation.

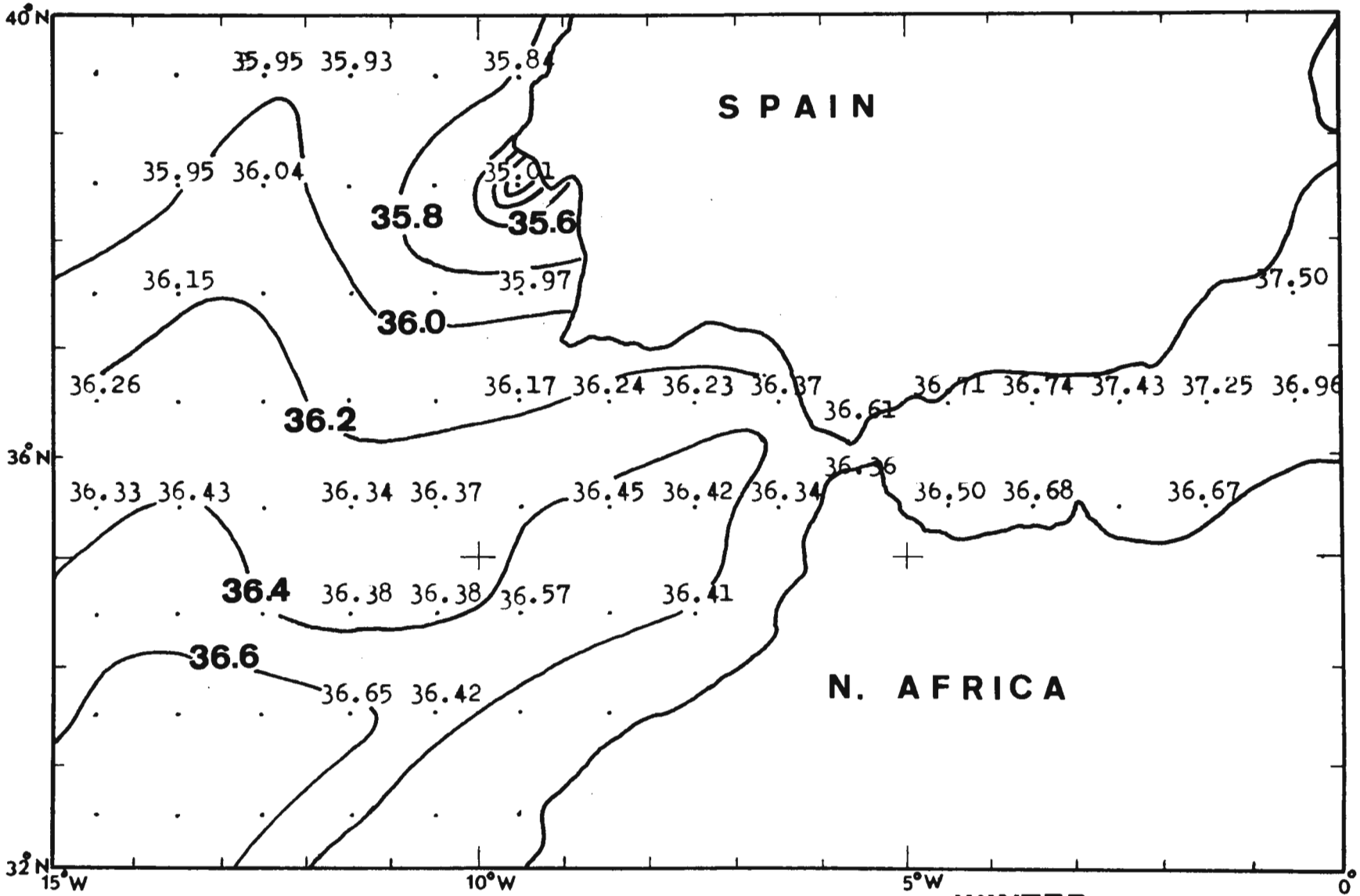


Figure 16a. Surface salinity(o/oo) **WINTER**

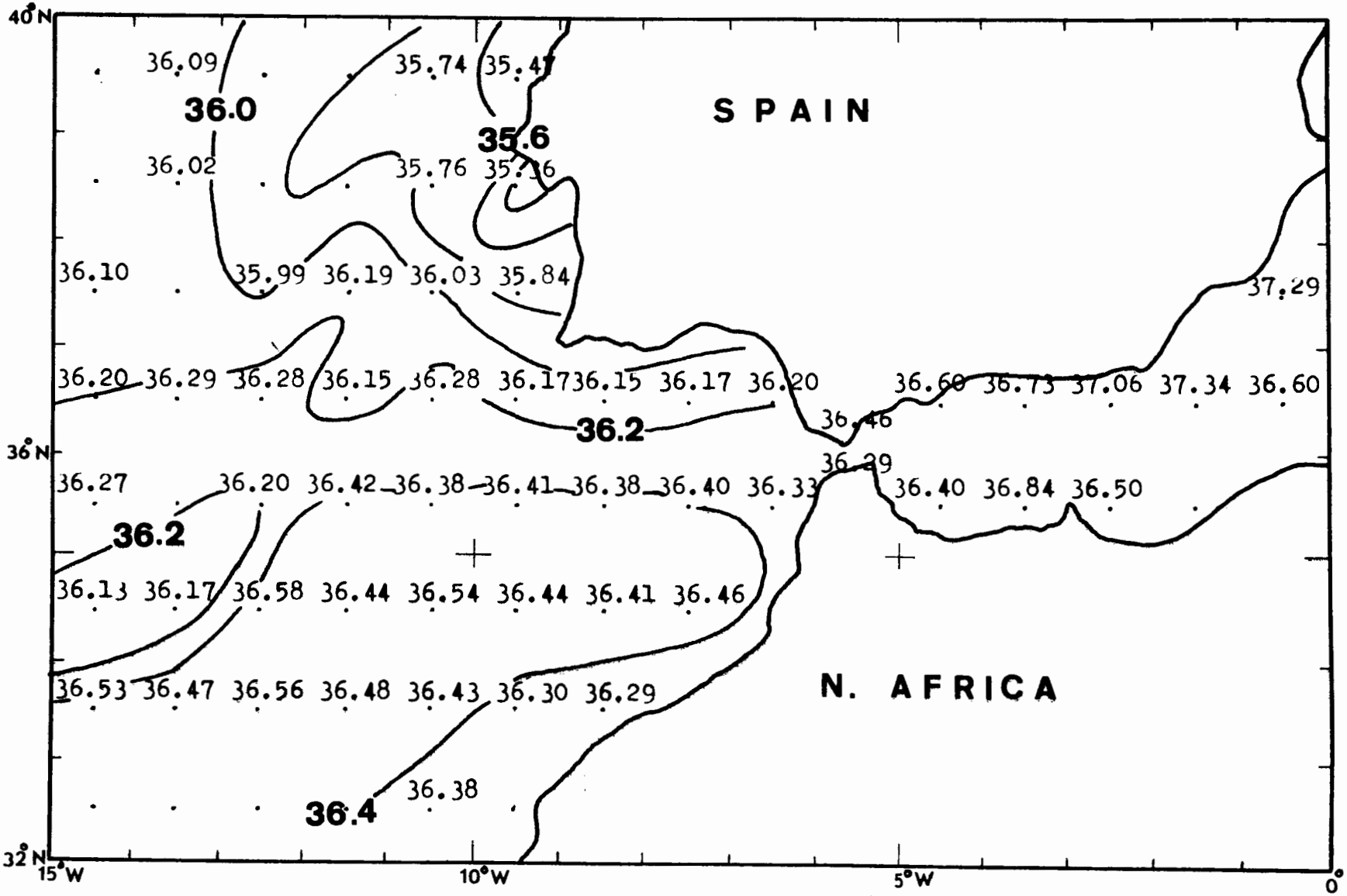


Figure 16b. Surface salinity(o/oo) SPRING

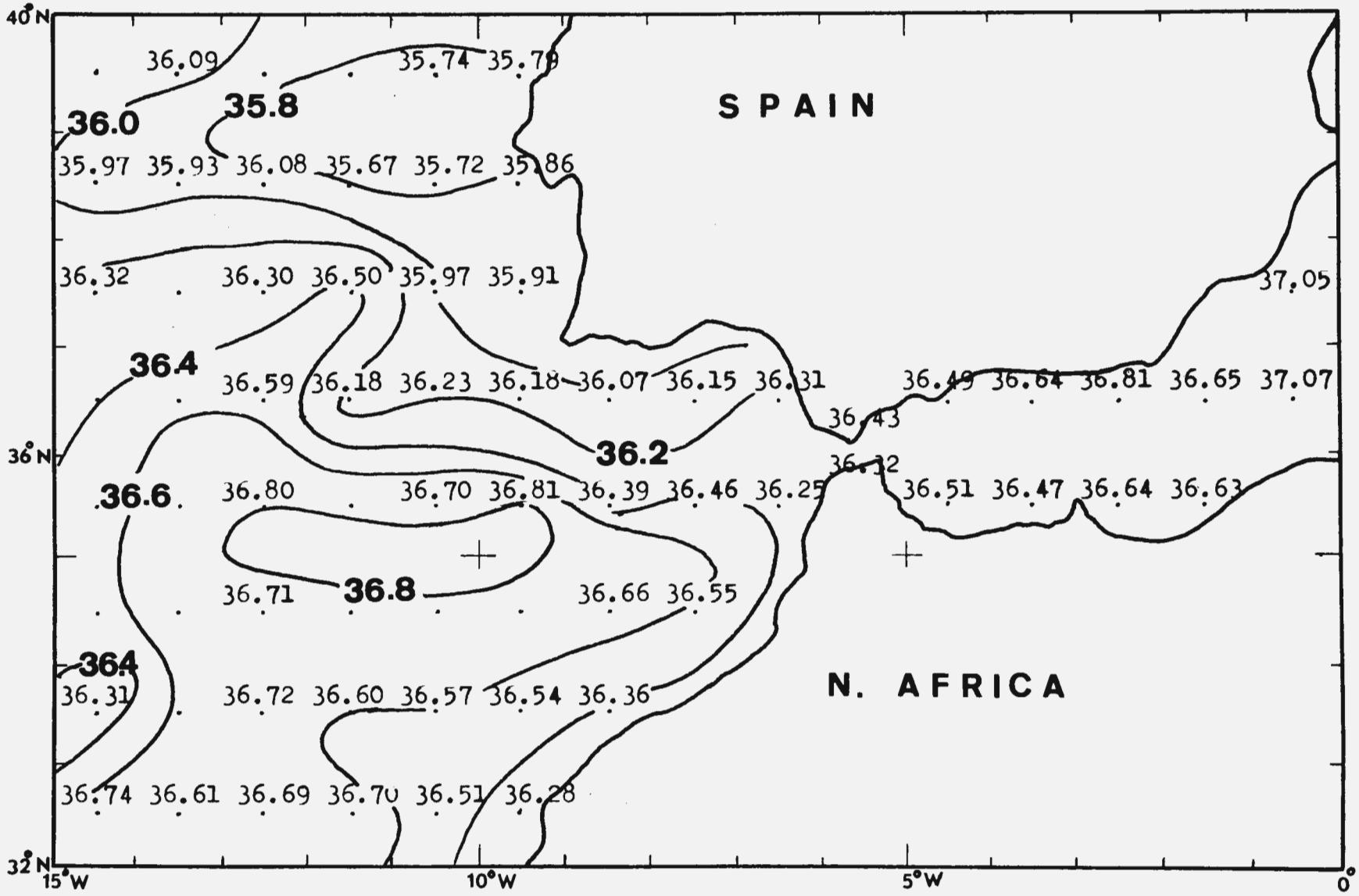


Figure 16c. Surface salinity(o/oo) **SUMMER**

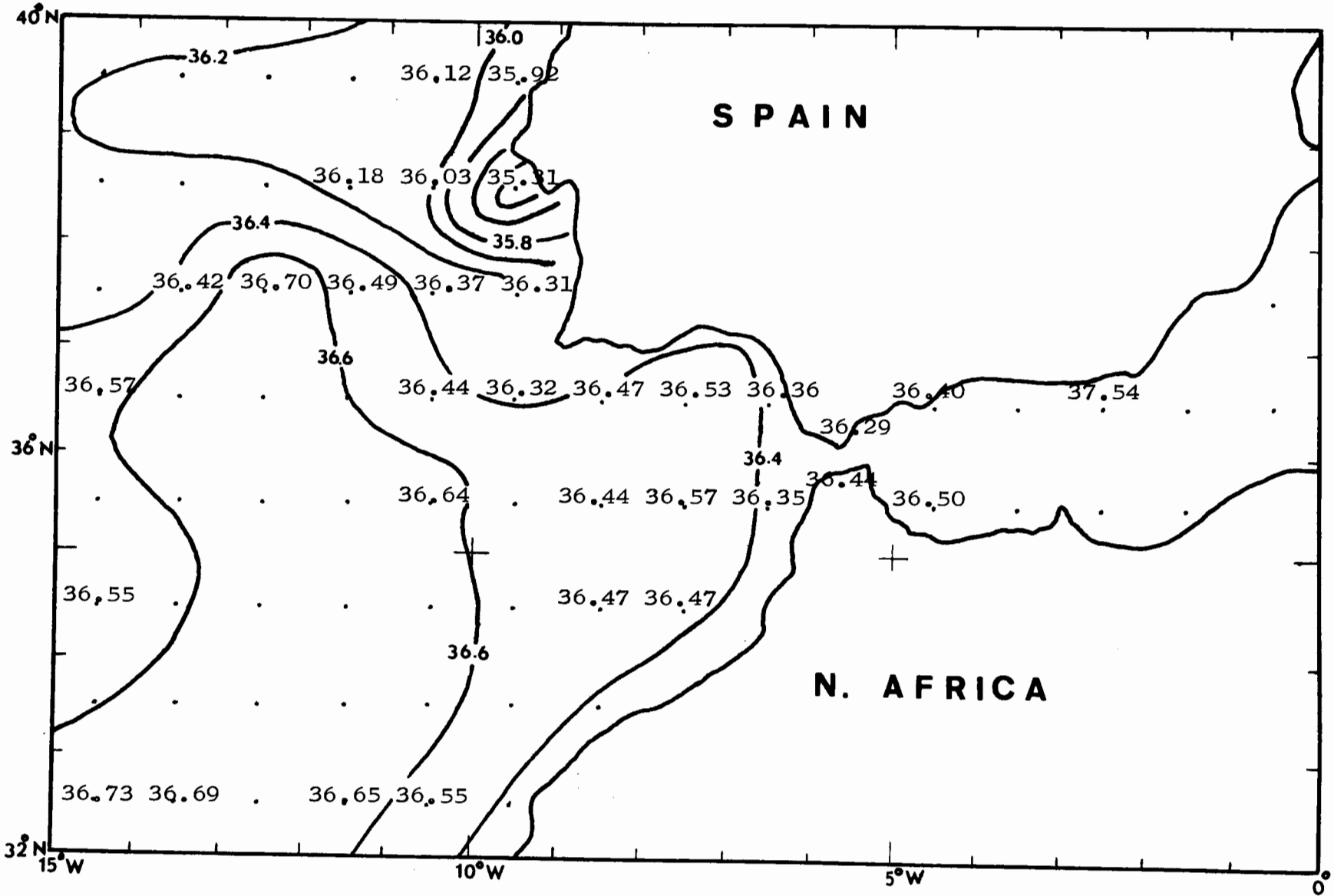


Figure 16d. Surface salinity(o/oo)

FALL

Along the western coast of Portugal a salinity minimum exists throughout the year but is least pronounced in the summer season. Undoubtedly precipitation and runoff contribute to the salinity minimum in fall and winter. The seasonal surface wind distribution, Figure 15, suggests "upwelling" in phase with that along the coast of Morocco, intermittently with maximum in summer season. Gougenheim and Romanovsky (undated) have demonstrated the occurrence of upwelling along the northwest coast of Portugal in August, using temperatures as an indicator.

(3) Salinity at 500 meters.

The isohaline patterns of Figure 17 show the effects of the high salinity Mediterranean Water as it spreads to the west and north. The horizontal salinity gradient west of the Gibraltar Strait is a maximum during the winter season suggesting this is the season of maximum outflow. Inside the Mediterranean Sea the 500-meter salinity is approximately 38.4 o/oo throughout the year, while outside the salinity varies between 35.6 and 36.5 o/oo at this level.

(4) Salinity at 1000 meters.

The extension of the deep tongue of Mediterranean Water into the Atlantic at a depth of 1000 meters is shown in Figure 18. As at 500 meters, the salinity gradient at 1000 meters also is strongest in the winter season. The flow of the Mediterranean Water is toward the west and then northwest around the southern coast of Portugal apparently under the influence of the Coriolis force. Lacombe and Tchernia (1960)

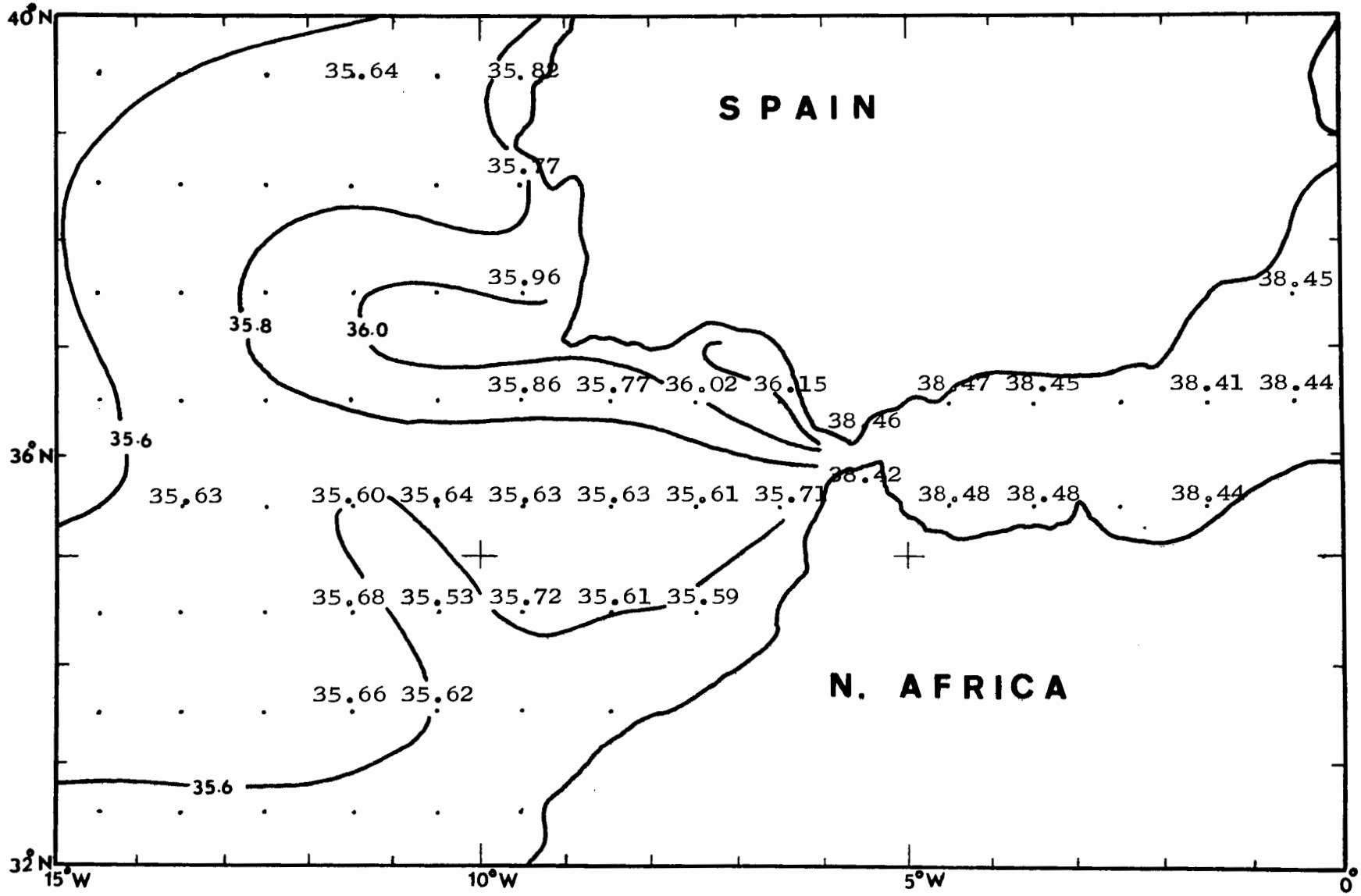


Figure 17a. Salinity at 500 meters(o/oo) WINTER

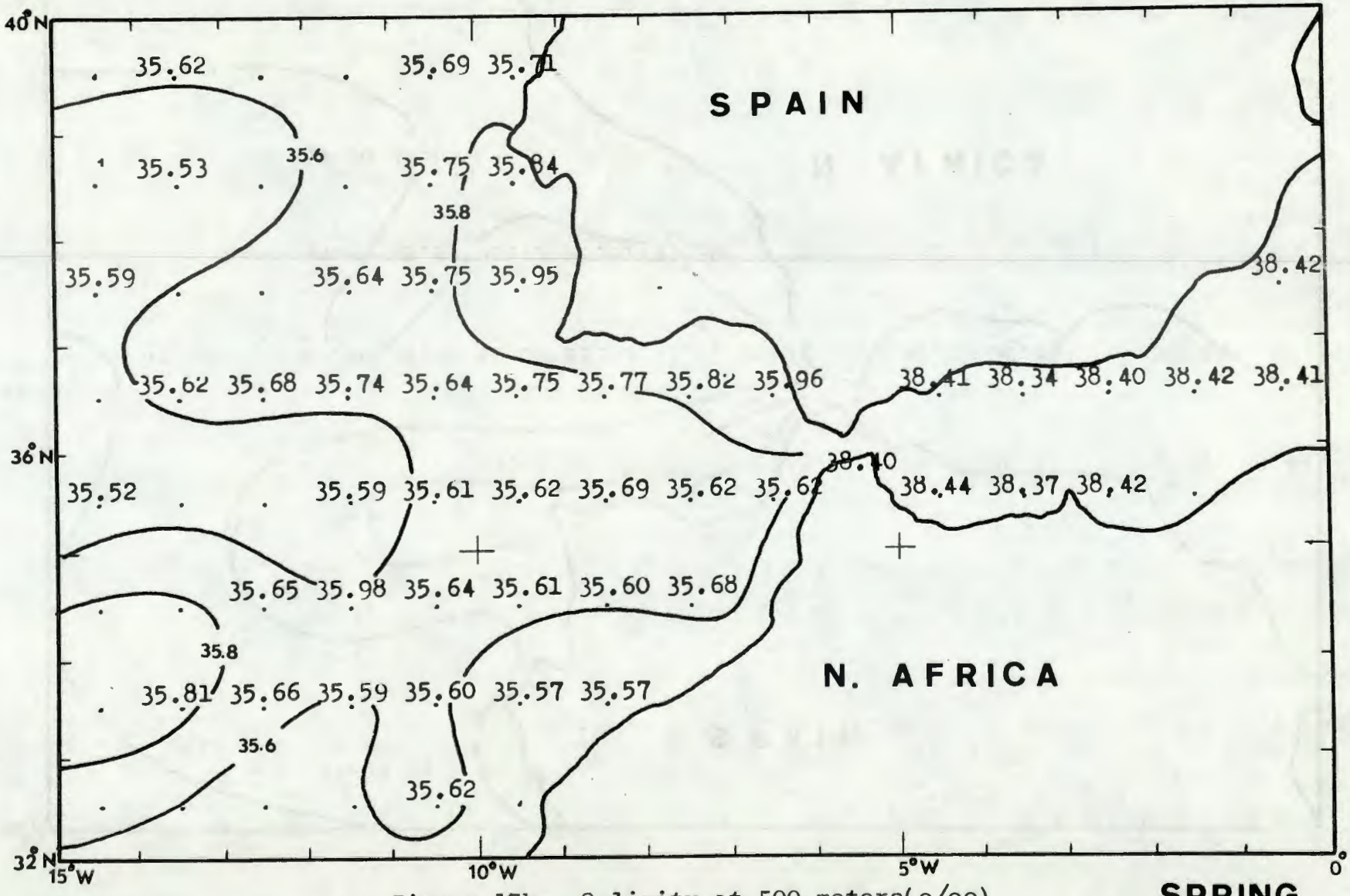


Figure 17b. Salinity at 500 meters(o/oo)

SPRING

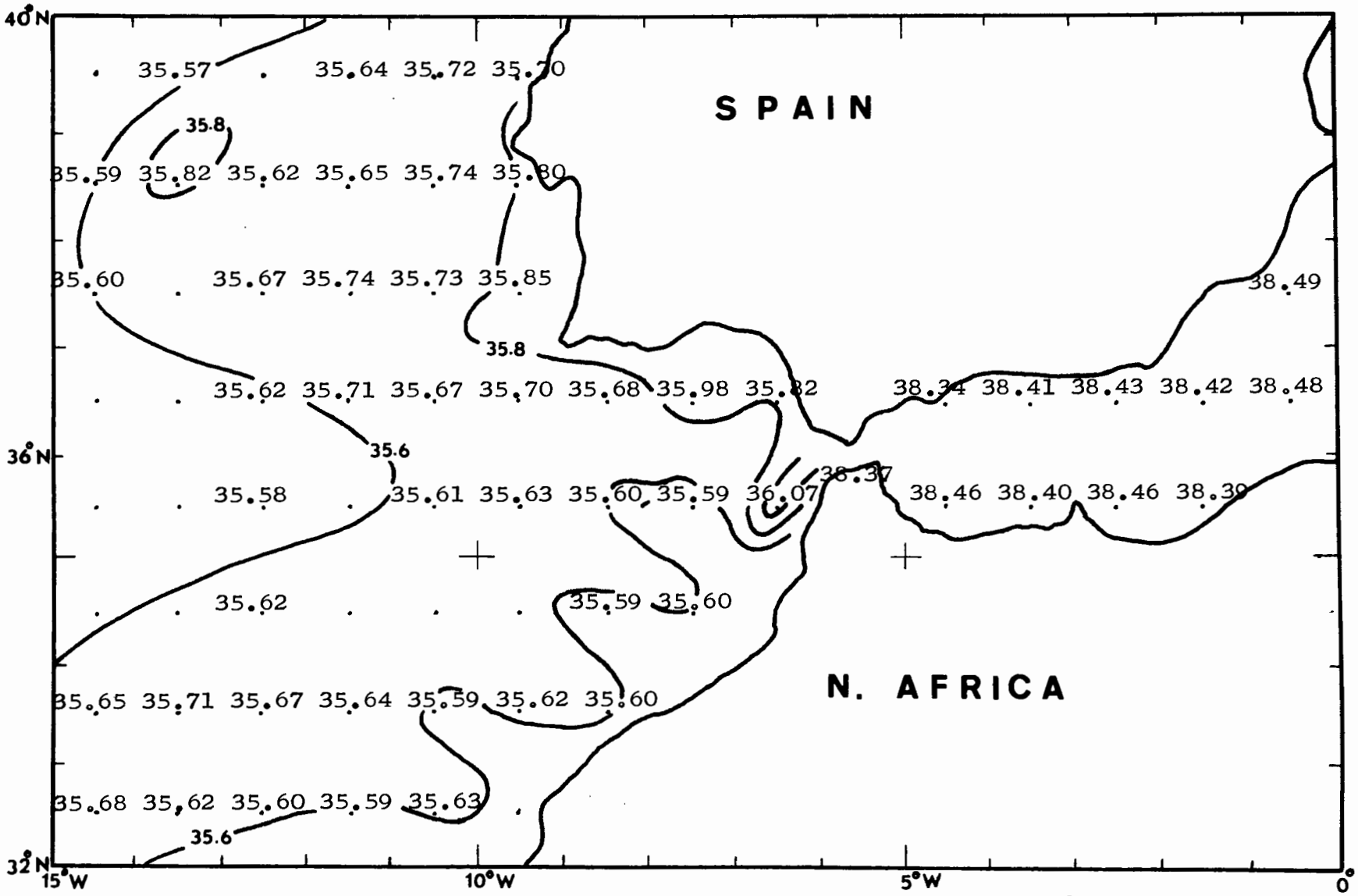


Figure 17c. Salinity at 500 meters(o/oo) **SUMMER**

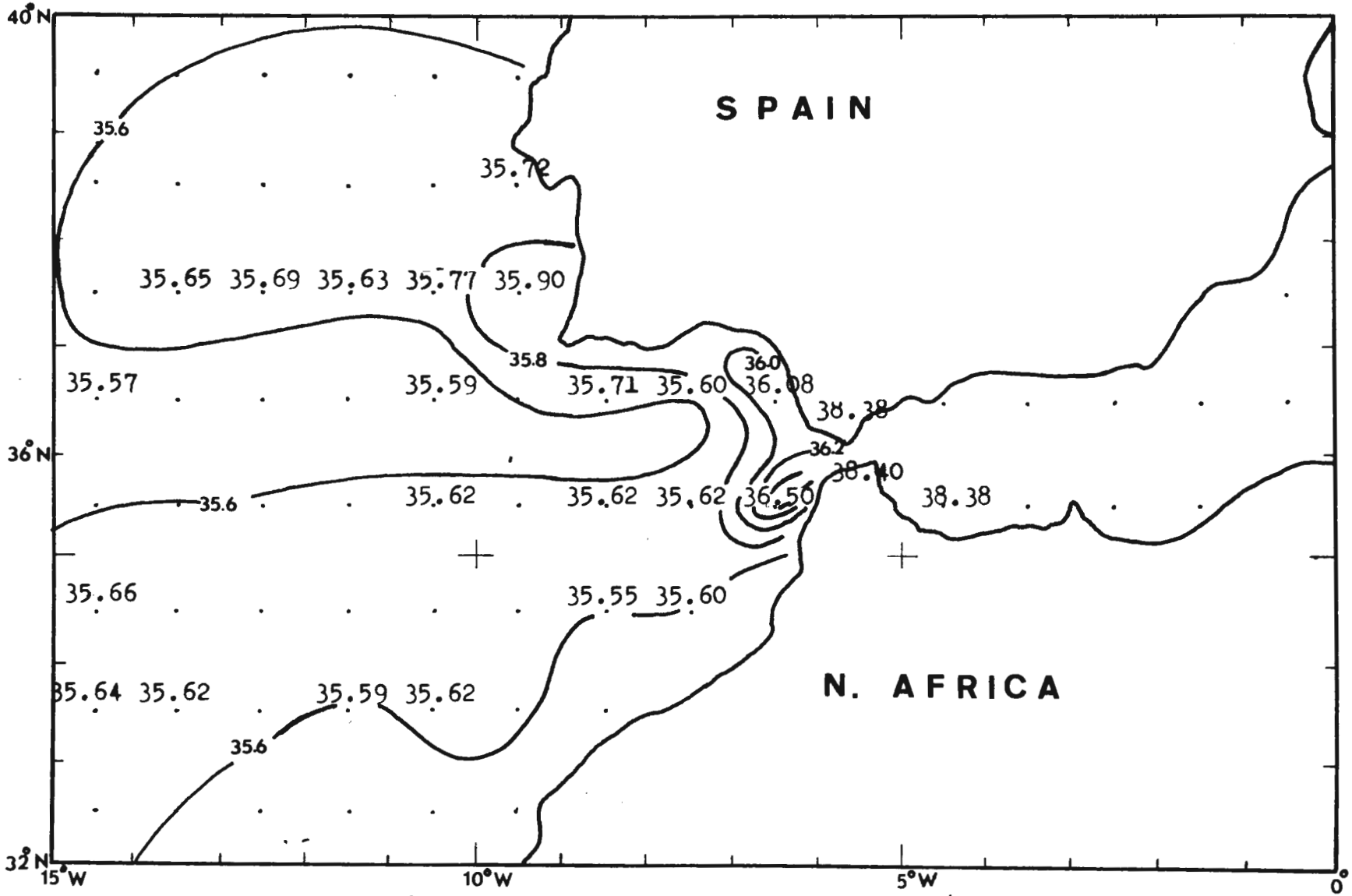


Figure 17d. Salinity at 500 meters(o/oo)

FALL

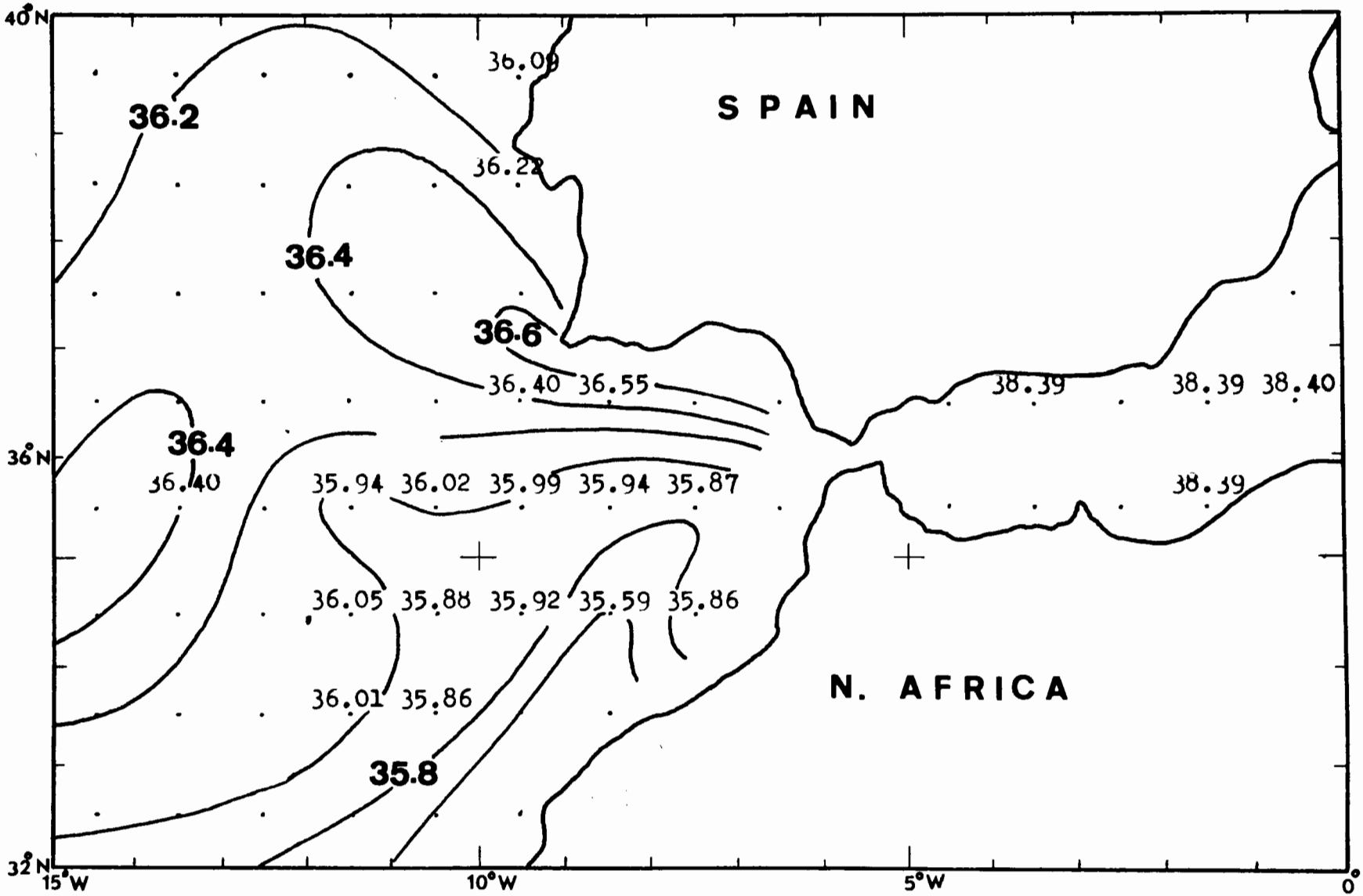


Figure 18a. Salinity at 1000 meters(o/oo) **WINTER**

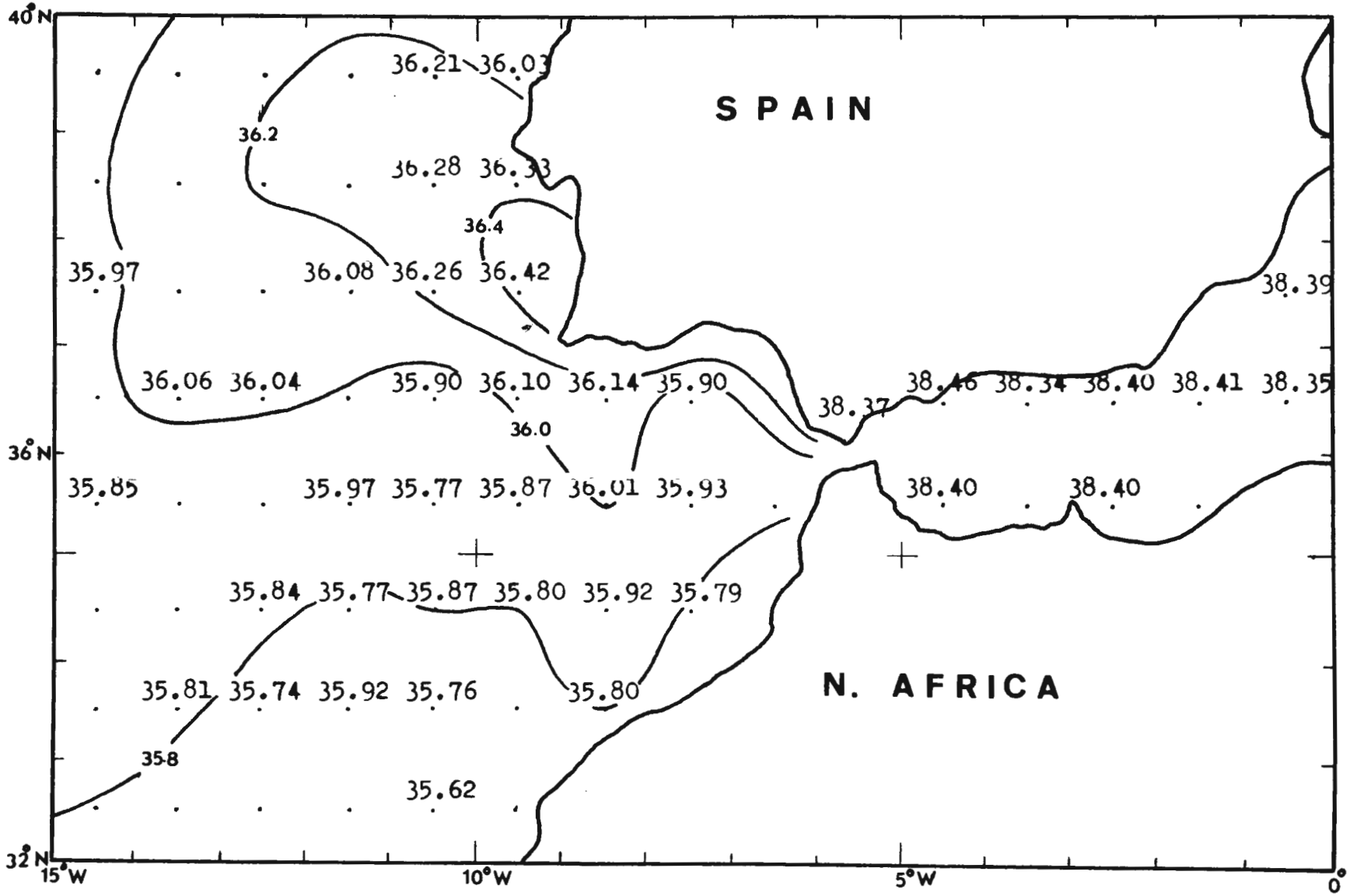


Figure 18b. Salinity at 1000 meters(o/oo) SPRING

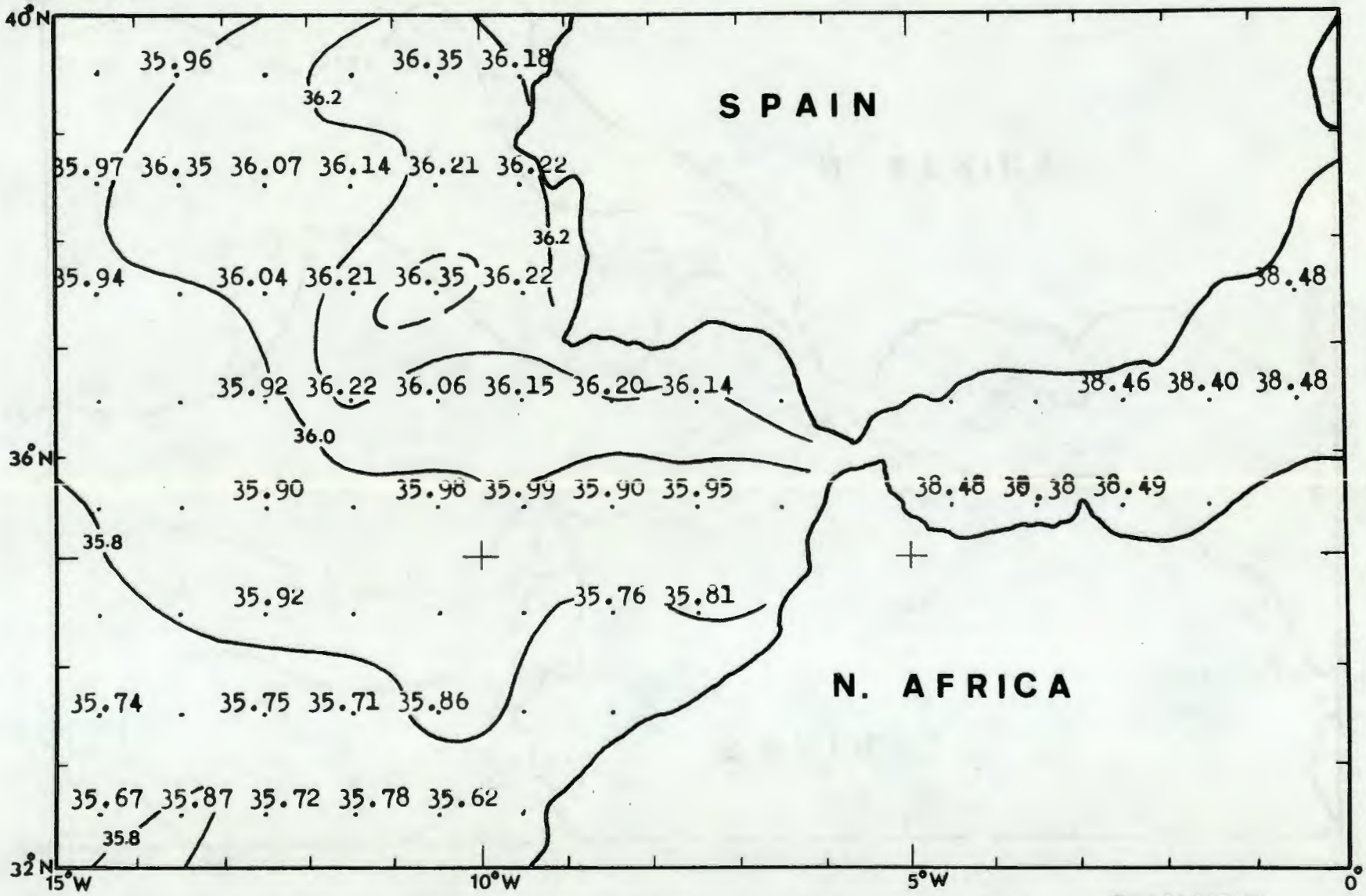


Figure 18c. Salinity at 1000 meters(o/oo) **SUMMER**

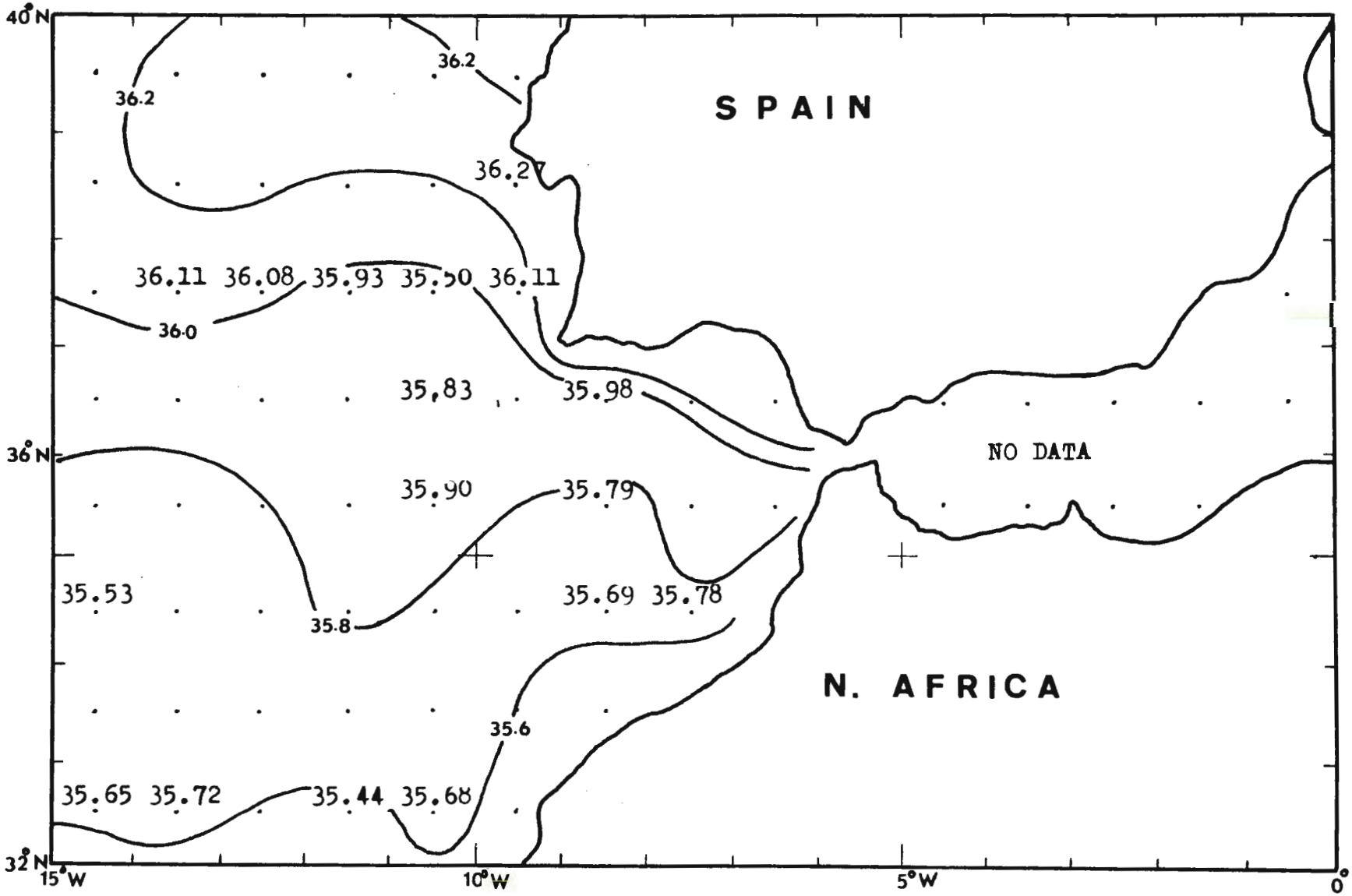


Figure 18d. Salinity at 1000 meters(o/oo)

FALL

illustrated the spreading of the Mediterranean Water for the summers of 1957 and 1958, Figure 19, which are very similar to the averaged summer section shown in Figure 18c. This similarity lends creditability to using averaged data on a seasonal basis and increases confidence in other sections prepared in this manner. The maximum salinities are found in the winter season off the southwest coast of Portugal. A significant decrease in the salinity maximum is noted for the spring and summer seasons. The salinity maximum in winter coupled with the strong salinity gradient provides further indication that winter is the season of maximum outflow.

(5) Layer of maximum salinity.

The seasonal maximum average salinity recorded for each one-degree Marsden square has been plotted and analyzed for the research area west of the Strait, as shown in Figure 20. The isohaline patterns indicate a high salinity core extending from the Strait with higher salinities and stronger gradient in the winter season. Scatter diagrams of seasonal maximum salinity versus depth of the maximum salinity were plotted but no correlation was found. The depth of the maximum salinity layer was plotted for each season but a consistent analysis of the data could not be obtained.

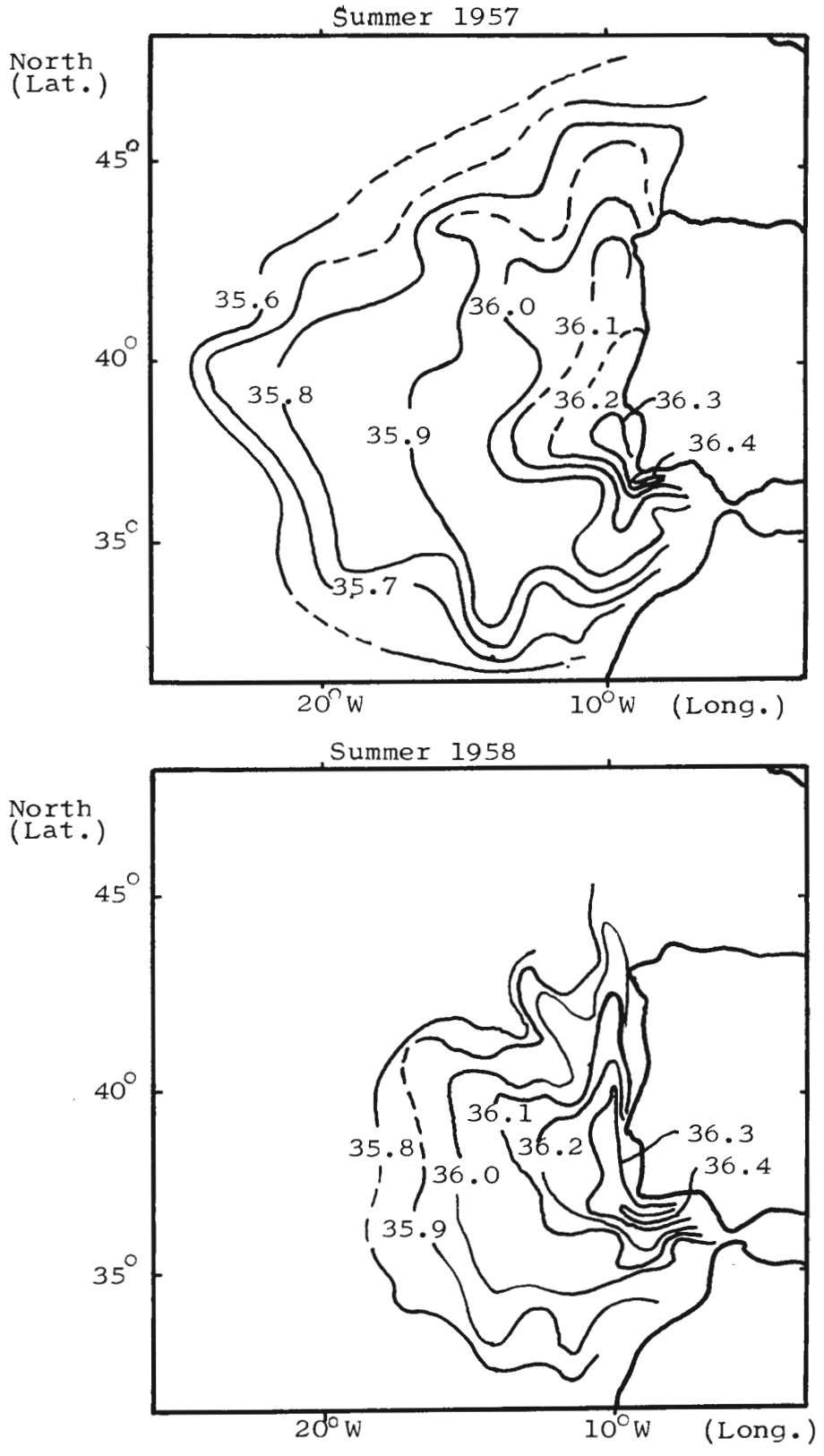


Figure 19. Salinity at 1000 meters for summers of 1957 and 1958. (after Lacombe and Tchernia, 1960)

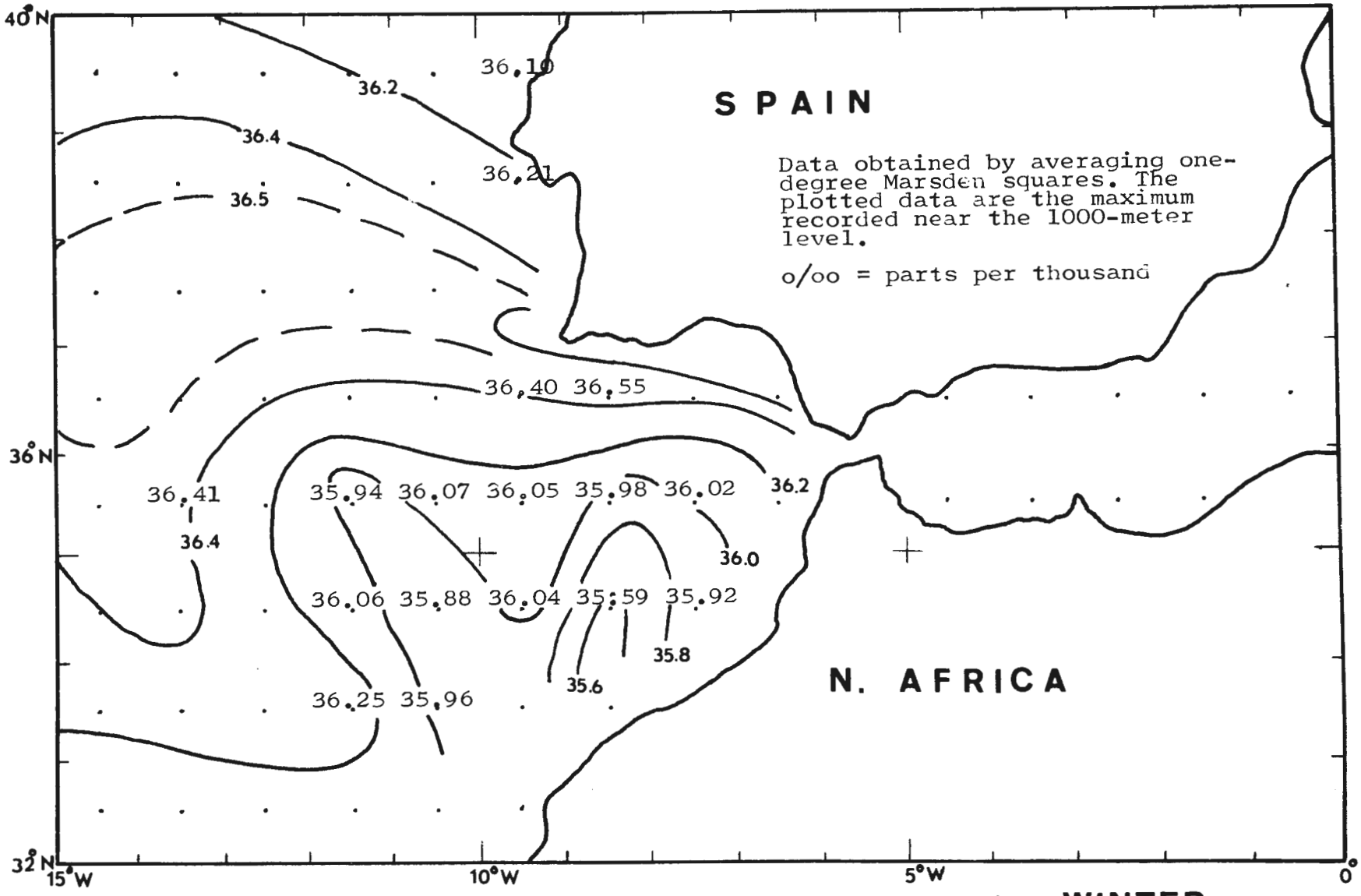


Figure 20a. Layer of maximum salinity(o/oo) **WINTER**

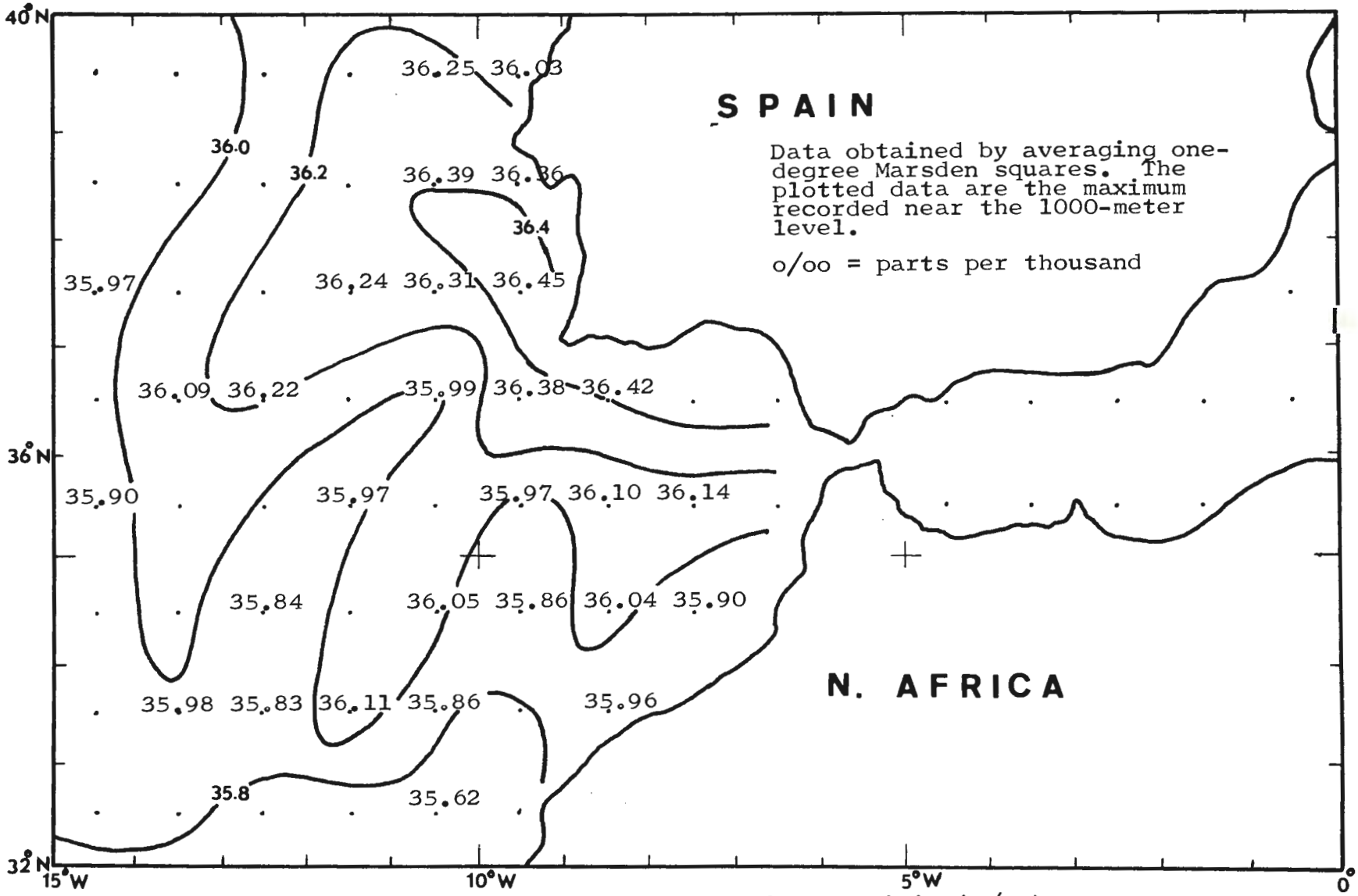


Figure 20b. Layer of maximum salinity(o/oo) **SPRING**

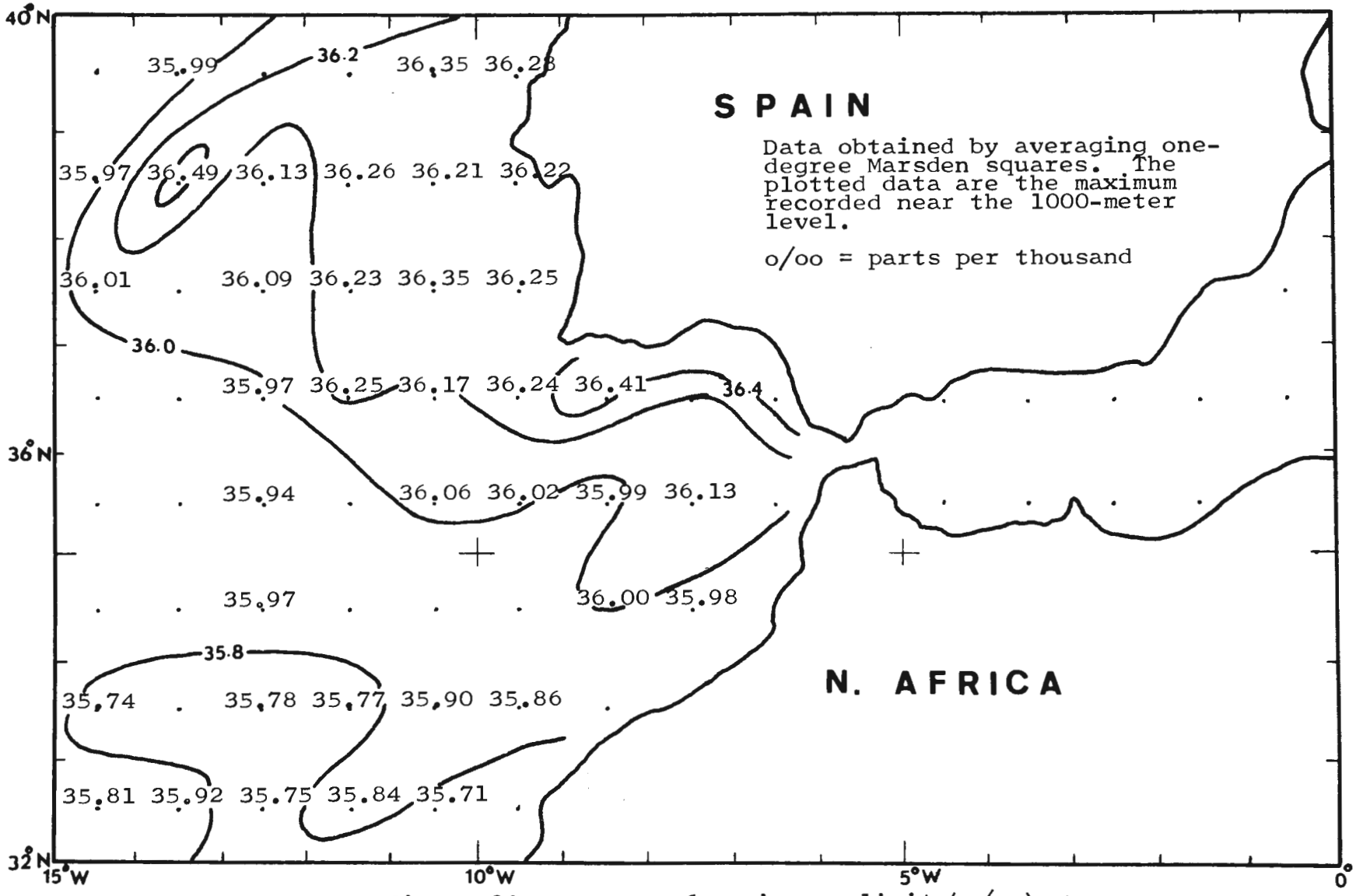


Figure 20c. Layer of maximum salinity(o/oo) **SUMMER**

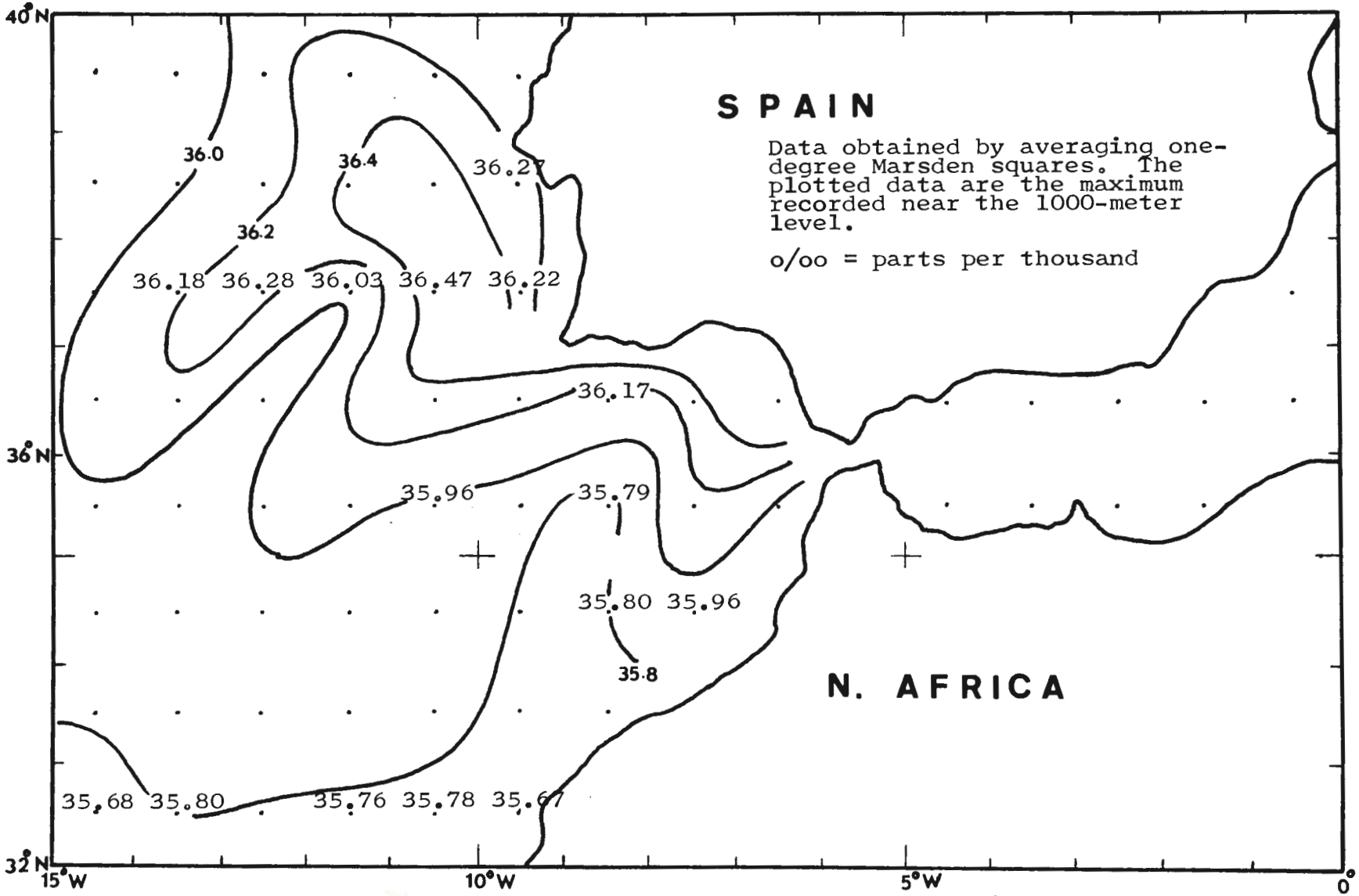


Figure 20d. Layer of maximum salinity(o/oo)

FALL

IV. COMPUTED CURRENTS

A. Dietrich's method.

Dietrich (1956) used the gradient current approach to calculate currents in a layer along the bottom slope of the Wyville Thompson Ridge. Dietrich's formula is used to compute the current in the bottom layer flowing along the bottom slope west of the Gibraltar sill.

$$U = \left[\frac{g h_2 \ (\bar{\rho}_2 - \bar{\rho}_1) \ \sin \alpha}{X \ \bar{\rho}_2} \right]^{1/2}$$

where:

g = gravity

h_2 = thickness of lower layer over the sill area

$\bar{\rho}_1$ = density of upper layer

$\bar{\rho}_2$ = density of lower layer

X = roughness constant

α = bottom slope

The formula is applied at the west sill, Cape Spartel, where the maximum depth is 375 meters. The average density was obtained by averaging the density data in the respective layers, assuming a variable interface of 125 meters in winter and 175 meters in summer. In this calculation the average slope (α) of the topography west of the sill is computed to be 0.008. The roughness constant (X) is taken as 0.3 as recommended by Hubert and Laevastu (1967). Seasonal densities, thickness of lower layer and computed current speed are shown in table 3.

Table 3. Seasonal layer densities, lower layer thickness and current speed (Dietrich's formula for bottom current over Gibraltar sill, X = 0.3)

Season	$_2$ (g/cm^3)	$_1$ (g/cm^3)	h_2 (m)	U (cm/sec)
Winter	1.02862	1.02776	250	23.4
Spring	1.02845	1.02792	225	17.4
Summer	1.02864	1.02843	200	10.8
Fall	1.02808	1.02746	225	18.8

There is considerable disagreement as to the correct value of the roughness constant, with suggested values ranging from 0.0025 to 0.3 (Dietrich, 1956). Dietrich calculated the bottom current over the Wyville Thompson Ridge using a roughness constant of 0.03. If this value is used with Table 3 data the computed currents of the bottom layer are as shown in Table 4.

Table 4. Seasonal current speed (data as in Table 3, except X = 0.03)

Season	U (cm/sec)
Winter	74
Spring	55
Summer	33
Fall	57

Using the bottom currents obtained by assuming a roughness constant of 0.03, mass outflow is computed for each season and the total compared with earlier work as shown by Wüst (1959). The cross-sectional area of the west Gibraltar sill, Cape Spartel, is used along with the interface depth assumed at 125 meters in winter, 175 meters in summer and 150 meters in spring and fall. The results of these calculations and comparisons are shown in Tables 5 and 6 respectively.

Table 5. Mass transport calculations (outflow, X = 0.03)

Season	Area (10^5 m^2)	U (m/sec)	Transport (10^6 m^3/sec	Transport (km^3/season
Winter	28.0	0.74	2.07	16,100
Spring	22.5	0.55	1.24	9,700
Summer	17.0	0.33	0.56	4,400
Fall	22.5	0.57	1.28	10,000

Table 6. Comparison of annual outflow (km^3/year)

Schott (19 ?)	Sverdrup (1946)	Wüst (1952)	Carter (1956)	Sears (1968)
51,890	52,981	52,980	28,976	40,200

These results show that mass transport calculations for the outflowing layer are reasonable, compared to previous work, when the roughness constant is taken as 0.03. Clearly, this formula can give only a

relative indication of the bottom currents because of the uncertainty of the roughness constant.

B. Geostrophic method.

Geostrophic calculations were made along a north-south line, to the east and west of the Strait of Gibraltar. Current determinations were made for the summer and winter seasons, as described by Lafond (1951), in an effort to obtain reasonable average values for currents through the Strait. Seasonal averaged values of temperature salinity and sigma-t were utilized from adjacent Marsden squares, along a north-south line, both to the east and to the west of the Strait. Results of calculations for the summer and winter are shown in Table 7, utilizing 175 meters and 125 meters as the level of no motion in summer and winter, respectively.

It is evident from these calculation that geostrophic current determination in the Strait area will give, at best, only an indication of the relative magnitude of flow. East of the sill in winter, the indicated flows above and below the interface are about equal in magnitude. West of the sill in winter, westerly flow is indicated in the lower layer with virtually no flow indicated in the upper layer. This is reasonable considering winter is the season of maximum precipitation and runoff along with minimum evaporation in the Mediterranean Sea; thus, less inflow of Atlantic Water is required to maintain the water balance of the Mediterranean Basin. East of the sill in the summer the indicated flow is difficult to relate to observed conditions. Comparing the winter and

Table 7. Geostrophic current calculations (cm/sec)
(- indicates flow towards the east)

(a) East of sill (Sta's 35.5N, 4.5W; 36.5N, 4.5W)

	Summer		Winter	
depth (m)	relative to 0 m	relative to 175 m	relative to 0 m	relative to 125 m
0	0.0	-7.5	0.0	-9.0
20	1.1	-6.4	1.5	-7.5
50	3.8	-3.7	4.1	-5.9
75	5.8	-1.7	6.4	-2.6
100	6.4	-1.1	8.2	-0.8
125	-	-	-	0.0
150	7.0	-0.5	10.3	1.3
175	-	0.0	-	-
200	7.8	0.3	11.3	2.3
300	8.6	1.1	12.1	3.1
400	6.4	-1.1	12.9	3.9
500	5.7	-1.8	13.2	4.2
600	5.5	-2.0	13.6	4.6
700	5.6	-1.9	13.9	4.9
800	5.6	-1.9	14.3	5.3
900	5.6	-1.9	15.0	6.0

(b) West of sill (35.5N, 6.5W; 36.5N, 6.5W)

	Summer		Winter	
depth (m)	relative to 0 m	relative to 175 m	relative to 0 m	relative to 125 m
0	0.0	-25.0	0.0	0.0
20	1.8	-23.2	0.0	0.0
50	6.5	-18.5	0.0	0.0
75	11.5	-13.5	0.0	0.0
100	14.1	-10.9	0.0	0.0
125	-	-	-	0.0
150	22.8	-2.2	-1.3	-1.3
175	-	0.0	-	-
200	31.8	6.8	-0.1	-0.1
300	40.8	15.8	7.8	7.8
400	42.3	17.3	20.0	20.0
500	46.3	21.3	26.5	26.5
600	47.5	22.5	25.8	25.8
700	44.7	19.7	22.0	22.0
800	42.8	17.8	22.0	22.0

summer results west of the sill shows inflow is greatest in summer, while outflow is greatest in winter. These calculations provide indications of flow but the limitations of the geostrophic method must be remembered. Lafond (1951) lists the following limitations to the accuracy of the geostrophic method:

(1) currents are relative to unknown reference level;

(2) accelerations have been neglected;

(3) frictional forces have been neglected;

(4) observations are considered synoptic;

additional error may be induced by the assumed distance between stations (60 nautical miles). Since the channel is almost 100 miles wide in the area for which the calculations were made, it is likely that a large per cent of the station data were taken near mid-channel although the exact location of data were not plotted or evaluated. Saelen (1963) compared geostrophic with observed currents off the western coast of Norway. He concluded that computed geostrophic currents have only a slight resemblence to the actual measured current in that coastal region.

C. Montgomery's method.

Montgomery (1938) has deduced flow patterns by use of the sigma-t surface as a surface of constant potential density; this approach was considered as a possible means to describe the spreading of the Mediterranean Water into the Atlantic Ocean. This technique cannot be used over the Gibraltar sill for the following reasons:

(1) there is a virtual discontinuity of sigma-t surfaces across the sill;

(2) surface dynamic factors are effective in moving sigma-t surfaces up and down in a seasonal cycle.

D. Measured currents.

Lacombe et al. (1964) anchored current meters in the Gibraltar Strait at various depths and recorded currents for the semidiurnal tidal period. One set of measurements was taken a short distance east of the Cape Spartel Ridge in September 1960, where the water depth is approximately 420 meters. Continuous recording current meters were placed at 10, 100, 200 and 300 meters and data were recorded for a 12-hour tidal cycle. In order to transform these data into a form suitable for calculation of mass transport, averages were computed for each data level. A current profile was then plotted and averaged by equal area approximation to give an averaged current for the inflowing and outflowing layers. These values were used along with the cross-section area above and below 175 meters to compute the mass transport through the Strait (see Table 8).

Table 8. Mass transport calculations from measured current profile. (level of no motion = 175 meters)

Summer	Area (10^5 m^2)	U (m/sec)	Mass transport (10^6 m^3/sec)
Inflow	51.7	0.20	1.03
Outflow	22.6	0.32	0.72

The relative volume of the transport can be checked using salt balance considerations for the Mediterranean Sea.

$$T_i S_i + T_o S_o = 0 ,$$

where:

T_i = mass transport into Mediterranean Sea;

S_i = salinity of inflowing water; (36.25 o/oo)

T_o = mass transport out of Mediterranean Sea;

S_o = salinity of outflowing water; (38.20 o/oo)

Using these values and considering an inflow of 1.03×10^6 m^3/sec, it can be seen that 0.98×10^6 m^3/sec outflow is required to maintain the salt balance of the Mediterranean Basin.

It is not known that a salt balance exists in the Mediterranean, but if it is changing it is doing so at a very slow rate; therefore, it is assumed that restrictions placed on the relative volume exchange are valid. It is noted that a relatively small change in the layer of no motion results in significant changes in the mass transport. For instance, assume the average boundary layer depth between the two currents is 150 meters, vice 175 meters. The resulting mass transport calculations are shown in Table 9.

Table 9. Mass transport calculations from measured current profile (level of no motion = 150 meters)

Summer	Area (10^5 m^2)	U (m/sec)	Mass transport (10^6 m^3/sec
Inflow	46.5	0.20	0.93
Outflow	27.8	0.32	0.89

V. EVALUATION

A. Synoptic versus seasonal sections.

There are no truly synoptic sections available for the Strait of Gibraltar area. The sections by Schott (1928) and Lacombe (1960) utilized data collected over a two to three month span in different years. There are a number of factors involved in the dynamics of the Strait that make it difficult, if not impossible, to obtain a synoptic section of the area. One of the important variables is the tides, which are semi-diurnal in nature. The tidal current is superimposed on the nontidal and wind drift currents of the Strait. The rise and fall of the sea surface with the tidal period causes a vertical oscillation of the interface between the Atlantic and Mediterranean water masses, and a corresponding change in the volume of flow in each layer. Internal waves are known to occur in the Strait with varying periods and amplitudes. Both tidal and internal wave phenomena cause large scale mixing across the interface. In addition, large eddies are known to exist near the eastern side of the sill due to the tidal variations and "upwelling" of the Mediterranean Deep Water.

This study has utilized averaged data on a seasonal basis to describe the distribution of salinity and temperature. The tidal effects and internal waves are assumed to be negligible by virtue of the averaging processes employed. This is probably a good assumption for the tides; however, it may not be realistic for the internal waves, since neither the generating mechanism of the internal waves nor the

frequency of occurrence is known. It is possible that the internal waves are related to atmospheric disturbances which are known to be more frequent and of greater intensity in certain seasons than in others.

B. General temperature, salinity and sigma-t structure.

The basic pattern of the averaged sections is in good agreement with those of Schott (1928) and Lacombe (1960). There is a vertical migration of the interface in the Strait area, resulting in an increased thickness of the inflowing layer in the summer season. Although this seasonal migration has not been established conclusively, there is evidence that it does occur (see Figure 10). An accurate description of the interface migration was not possible due to large variations of temperature and salinity present in the surface layers. These variations probably are not real but appear in the analyses due to data insufficient to establish realistic averages.

The interface between the inflowing and outflowing layers is maintained throughout the year by vertical motions in the water masses east and west of the sill area. A large volume of the mixed water is carried back into its respective basin at a different level due to its new density acquired through the mixing process. This is essentially the system presented by de Buen (1926), except the subsurface outflow was not included as a part of the model.

The primary atmospheric parameter affecting the area of study is the wind velocity. Along the coasts of Morocco and the Iberian Peninsula adjacent to the Strait, surface winds exert a seasonal

influence on the movement of the surface water. A salinity minimum exists along the Moroccan coast throughout the year; it is most pronounced in summer, indicating that "upwelling" of less saline water is at a maximum in this season (see Figure 16). This argument is supported by the increased speed of the surface winds from the northeast during the spring and summer. Along the west coast of Portugal, evidence of "upwelling" is not well defined, although the wind regime infers the same general pattern is to be expected as along the Moroccan Coast.

C. Seasonal water exchange.

Comparison of seasonal sections provides several indications that winter is the season of maximum outflow of the high salinity Mediterranean Water.

(1) The layer near 1000 meters, west of the Strait, has a slightly increased salinity maximum in winter (see Figure 10).

(2) The horizontal salinity gradient is strongest, west of the Strait, at all levels (surface, 500, and 1000 meters) in the winter (see Figures 16, 17 and 18).

(3) The high salinity water near 1000 meters, west of Portugal, has its maximum salinity in winter and spring (see Figure 14).

The results of computed currents for the Strait area are questionable. The geostrophic method is of little value in this region, primarily because of the inherent assumptions of the method, which in general were not satisfied.

Dietrich's formula, with a roughness constant of 0.03, provides the most reasonable values of current speed in the bottom layer; in fact, the computed summer outflow (33 cm/sec, Table 4), agrees well with the measured summer profile (32 cm/sec, Table 8), by Lacombe et al. (1964). In addition, the annual total mass transport (outflow), using currents computed by Dietrich's formula along with the cross-sectional area, is in good agreement with earlier work as shown in Table 5. These agreements provide a degree of confidence in Dietrich's formula for use in current computations for the other seasons of the year.

The seasonal outflow, as computed from Dietrich's formula (Table 5), shows an increase by a factor of four, from summer to winter. This factor appears high and is probably due to the assumption of 125 and 175 meters as the depth of the interface for winter and summer respectively. It is likely that the average depth of the interface is somewhere between these two extremes, which would alter the calculated mass transport.

VI. CONCLUSIONS

The prepared sections of salinity, temperature, sigma-t and atmospheric parameters provide indications of seasonal flow variation through the Strait of Gibraltar. The following conclusions resulted from these indications and the computed currents in the Strait:

(1) The Mediterranean Water has a maximum outflow in winter and a minimum in the summer season.

(2) The Atlantic water has a maximum inflow in the summer and a minimum in the winter season.

(3) Compared to earlier work, the computed volume of water exchange across the sill of 40,200 km^3 is reasonable. However, the ratio of the summer to winter volume exchange, shown in Table 5, is doubtful.

(4) The Mediterranean Water is deflected to the north as it leaves the Strait, along the southern Iberian Peninsula.

(5) The salinity maximum area near 1000 meters, west of Portugal, is maintained throughout the year with only a slight increase in salinity in winter and spring.

(6) The seasonal wind patterns produce "upwelling" along the coasts of Morocco and Portugal with a maximum in the summer; however, upwelling probably occurs intermittently throughout the year depending on the synoptic situation.

VII. RECOMMENDATIONS FOR FURTHER RESEARCH

Measurement of currents and depth of the interface across the sill area is needed during periods of high winds to determine the character and magnitude of any changes in these two variables. The currents probably could be obtained by anchoring continuous recording meters along the ridge at various depths. A towed thermistor chain could be used to record the variation of the interface with changing atmospheric conditions.

The generating mechanism of the internal waves across the sill area is not well understood. Perhaps simultaneous temperature records, obtained by thermistor chain east and west of the Strait, could be statistically evaluated to help determine the generating mechanism.

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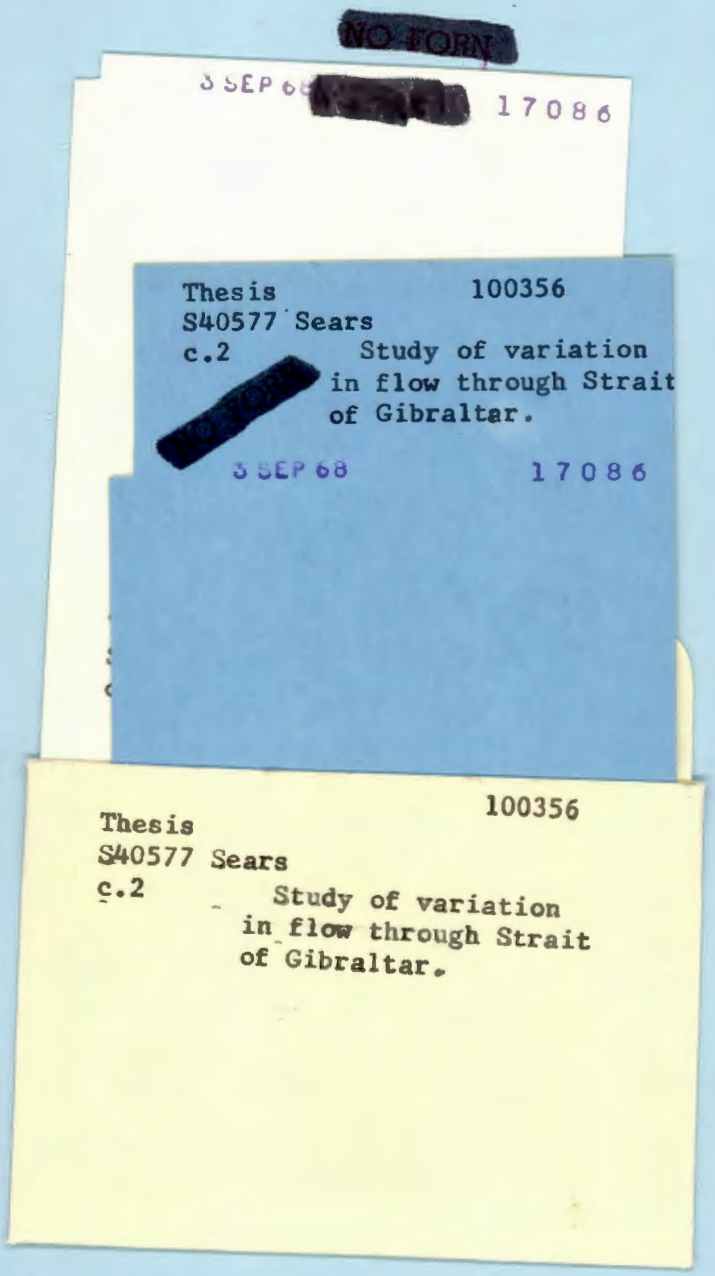
13. ABSTRACT

Averaged oceanographic station data are used to describe the seasonal variation of salinity and temperature in the Strait of Gibraltar area. Seasonal sections of salinity suggest that winter is the season of maximum outflow of the Mediterranean Water, and that summer is the season of maximum inflow of the Atlantic Water. The seasonal sections show how the high salinity water is deflected to the north along the Iberian Peninsula, and show that the salinity maximum near 1000 meters, west of Portugal, is maintained through all seasons.

The seasonal currents of the bottom layer west of the sill are computed. These are used with the cross-sectional area acrosss the strait to compute the seasonal mass transport, of the outflowing layer. The total annual outflow thus obtained compares favorably with earlier calculations.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
SALINITY, SEASONAL						
MASS TRANSPORT						
SEASONAL CURRENTS						
ANNUAL INFLOW						
ANNUAL OUTFLOW						
GIBRALTAR						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